Advanced Work in
IRCRAFT ELECTRICIT

1945 EDITION

NAVY TRAINING COURSES

ADVANCED WORK IN AIRCRAFT ELECTRICITY

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PREFACE

This book was written for the enlisted men of Naval Aviation. It is one of a series of books designed to give them the necessary information to perform their aviation duties.

A knowledge of advanced work in aircraft electricity is of primary importance to Aviation Electrician's Mates in the higher ratings. But they should approach this book only after they are thoroughly familiar with the material contained in FUNDAMENTALS OF ELECTRICITY and AIRCRAFT ELECTRICAL SYSTEMS. That material provides a background for understanding advanced work in aircraft electricity.

Starting with a discussion of vacuum tubes, this book takes up measuring instruments and aircraft electrical instruments. Then it follows with a study of Kirchoff's Laws, d-c armature winding, theory of a-c circuits. There is a discussion of motors and generators, and power transformers. In conclusion, there is a section on electric propellers, electrical ordnance equipment, and aircraft electrical checks.

As one of the NAVY TRAINING COURSES, this book represents the joint endeavor of the Naval Air Technical Training Command and the Training Courses Section of the Bureau of Naval Personnel.

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ADVANCED WORK IN AIRCRAFT ELECTRICITY

CHAPTER I

VACUUM TUBES

DIODE AND TRIODE TUBES

Remember how proud you were when you learned to drive an automobile? With a twist of your wrist you could shift gears and turn the wheel and make the car go where and how you wanted it to go. And with a slight pressure of your foot, you could stop it or speed it up. You—weight, perhaps 140 pounds—were controlling a car weighing about 20 times as much as you did.

That, in a general way, is how the two circuits through a vacuum tube work. The input circuit uses a small voltage to control a large current in the output circuit, yet there is no interchange of current or voltage from one circuit to the other.

CATHODE AND ANODE

In figure 1, you'll see a diagram of the parts of a vacuum tube. The filament, called the CATHODE, is quite similar to the filament of an electric light bulb.

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When a current is fed from a 6-volt "A" battery through the wire filament, the resistance of the wire to the current causes the wire to become red hot. When any metal gets hot, it gives off electrons, or negatively charged particles. You know that all matter, including metal, is made up of atoms, and that the atoms contain electrons and protons.

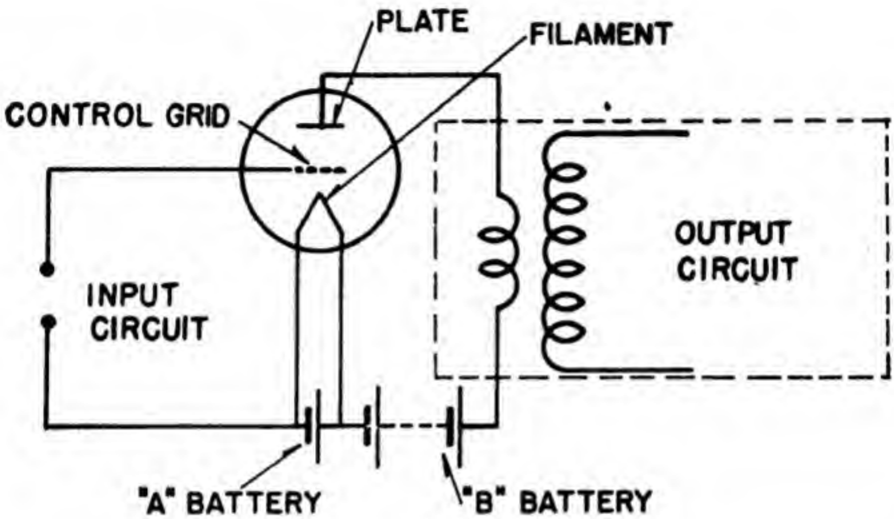


Figure 1.—Parts of a triode.

These electrons which are driven off from the metal filament gather in a cloud or SPACE-CHARGE around the filament. And in a simple, one-element "vacuum tube," such as a Mazda electric light bulb, nothing further happens to these electrons. They are driven out of the filament, and hang in a cloud around the vicinity of the filament.

But put a second element into your vacuum tube, and you make it a DIODE or two-element tube. Put a plate, called an ANODE, opposite and facing the filament. Next, connect the plate to one leg of the filament, and insert a galvanometer in this circuit. Now you'll find that when you close the switch and let current flow through the filament, you'll get a deflection of the galvanometer. The current through the meter is produced by the flow of electrons from

the hot filament across the vacuum to the cool anode. A small number of the electrons driven off the filament shoot on out through the space charge and land on the anode. Once these negative electrons land on the anode, they bump on around the wire, through the meter, and into the filament wire to replace the electrons that are being driven off.

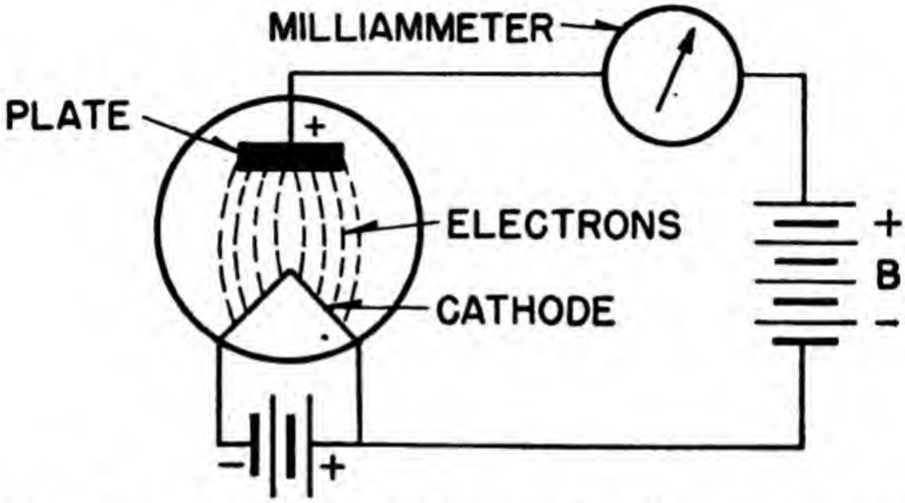


Figure 2.—Plate of vacuum tube is positive, hence electrons flow from filament to plate, and current flows through the circuit.

However, you can speed up the flow of electrons from cathode to anode. Put a second battery in the circuit. Connect this plate battery or "B" battery in the conductor circuit from anode to cathode, hooking the plus terminal of the "B" battery to one side of the plate. By connecting the battery up this way, you actually draw electrons away from the plate when you close the circuit, and increase the attraction of the plate for electrons from the cathode.

But if you connect up the "B" battery the other way around, that is, negative terminal to plate, you only put more negative electrons from the battery on the plate. There is no electron flow from cathode to anode, since the anode is already full of electrons. The electrons on the anode repel the electrons that shoot off from the hot cathode.

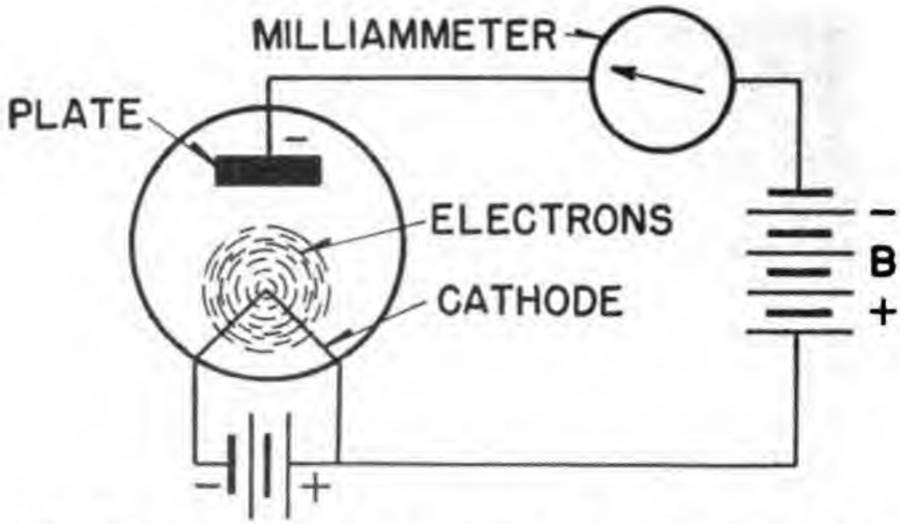


Figure 3.—Plate of vacuum tube is negative, and no electrons flow from filament to plate. No current flows.

You can now see what will happen if you feed an a. c. to the anode of this two-element vacuum tube. When the positive alternation of the a. c. is impressed on the plate, electrons will flow from cathode to plate. But when the alternation of the a. c. becomes NEGATIVE, which it is half of every cycle, no electrons will move, and no current will flow through the meter.

Remember this point—you already know about the confusion Ben Franklin caused when he decided that current flows from positive to negative. We know that the ELECTRONS in a circuit MOVE FROM NEGATIVE TO POSITIVE. But to avoid too much confusion, we still SAY that CURRENT moves from positive to negative, or in the OPPOSITE direction to electron flow.

CATHODE, ANODE, AND GRID

Next put a third element in your vacuum tube. Put a fine-mesh fly-screen between the cathode and plate, over close to the cathode. This third element is called the GRID. A three-element vacuum tube is a TRIODE. All the electrons that move from the hot filament to the anode must pass through the openings in this grid.

If you connect this grid to the positive side of a battery, electrons from the cathode would be drawn to the grid, and a negative connection of battery to grid would drive the electrons away from the grid. You can use this grid to control the flow of electrons from the cathode to the plate. You have put a gate across the electron path, and by charging this gate or grid with a positive charge, you open the gate and help pull the electrons through from cathode to anode. By charging the grid negatively, you repel the negative electrons that have left the filament to go to the anode. So you've closed the gate. No electrons flow across the vacuum, and no current flows in the plate circuit.

A very small voltage on the grid will control a large voltage across the tube from cathode to plate. The grid is close to the filament, and has a strong influence on the electrons being given off by the filament. For this reason, you can feed a weak a-c voltage into the tube and take out a strong reproduction of its peaks and dips supplied by the 45–volt "B" batteries.

AMPLIFIED WAVES

Now look at figure 4. It shows you how the small variations or dips and peaks in the small grid voltage are carefully duplicated in pattern by the large variations or dips and curves of the amplified current flowing in the plate circuit. Remember that the voltage in the grid circuit is a small one, and that the current in the plate is a large one, supplied by the 45-volt "B" batteries. But see how the curve of current variations in the plate circuit is simply a six-foot-six version of the five-foot-two squiggles in the input of grid circuit. Again, you are making the automobile start, turn right or left, and slow down simply by pressing the pedals or turning the wheel.

But wait! You'll have to fix one thing if you want your vacuum tube to play ball with you on this matter of making the amplified current wave resemble its little half-pint papa. You have to get rid of a thing called GRID CURRENT, or your amplified current wave will have a knob on its head, or an extra leg, or some other defect that its papa did not have.

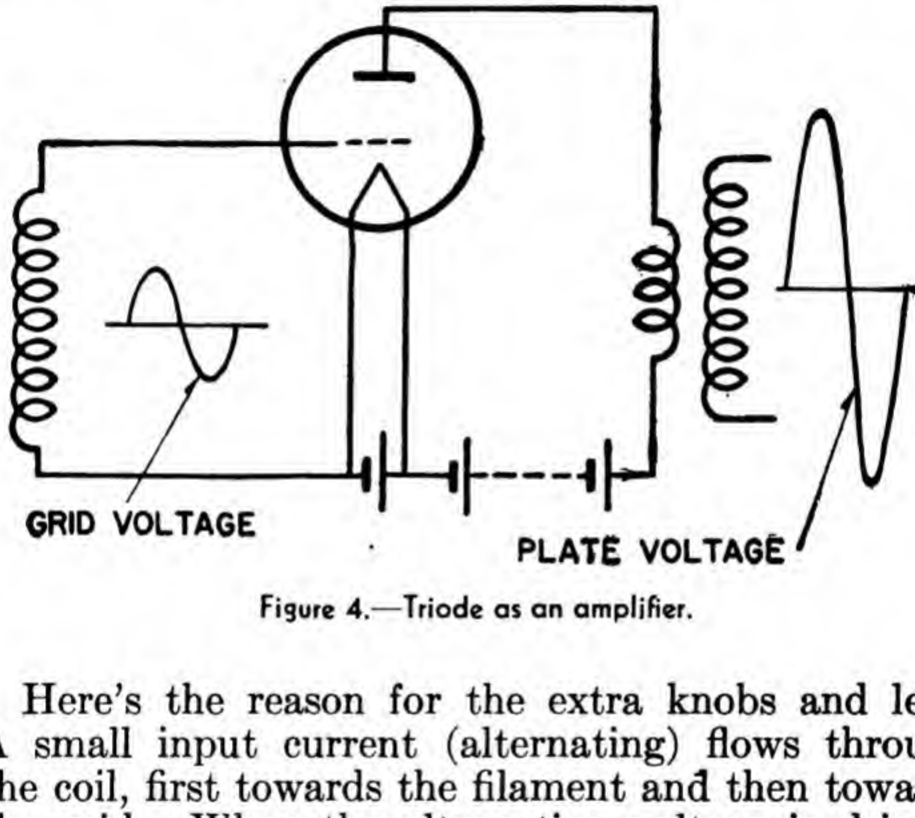


Figure 4.—Triode as an amplifier.

Here's the reason for the extra knobs and legs. A small input current (alternating) flows through the coil, first towards the filament and then towards the grid. When the alternating voltage is driving electrons towards the grid, the grid becomes negatively charged, and tends to reduce the flow of current between the filament and the plate, in proportion to the size of the grid's negative charge. But when the alternating voltage is driving electrons away from the grid (towards the filament), the grid becomes POSITIVELY charged and tends to increase the flow of current between the filament and the plate. If this increase was proportional to the size of the grid's positive charge, there would be no extra knobs and legs on the output current curve.

However, because the grid is now positive, it attracts some of the electrons passing from the filament to the plate. As a result, the increase of output current is NOT proportional to the size of the grid's positive charge.

Here's how to keep the output current almost exactly proportional to the input voltage. Use a "C" battery, hook it into the grid circuit, and your troubles are over. The "C" battery supplies a permanent negative charge to the grid. Now, the negative alternation of the input voltage makes the grid slightly more negative and the plate current is reduced PROPORTIONATELY. And the positive alternation of the input voltage makes the grid slightly more positive (or slightly less negative—which is the same thing) and the plate current is increased PROPORTIONATELY.

Result—your output alternating current wave again resembles its papa; no knobs, no extra legs, no hash in the phones.

The "C" battery, also called the GRID-BIAS BATTERY, must be of small enough voltage so that it won't completely stop the flow of electrons from the filament to the plate. It must be large enough so that the grid will not become charged positively with respect to the filament and attract electrons, thereby putting extra knobs and legs in the output current.

REPLACE THE "C" BATTERY

But suppose you don't want to bother with "C" batteries—they wear out, are heavy and fragile. All right, put a fixed condenser and resistor in the grid circuit. Here's how this set-up works. When the input current goes negative, plate 1 of the condenser in figure 5 (*A*) takes on a negative charge. Some of the negative electrons on the other plate

the condenser are repelled and driven over into the grid, making it negative. When the input circuit becomes positive on the next cycle of alternation, plate 1 of the fixed condenser in figure 5 (*B*) becomes positive, the negative electrons out on the grid are attracted back to plate 2 of the condenser, and the grid is positive again.

As the negative electrons from the filament rush across to the plate, a few of them prefer to stay on the positive grid. But they don't get a chance to stay on the grid. They are pulled over into plate 2 of the fixed condenser, adding a few more negative electrons to the crowd already on plate 2. The next

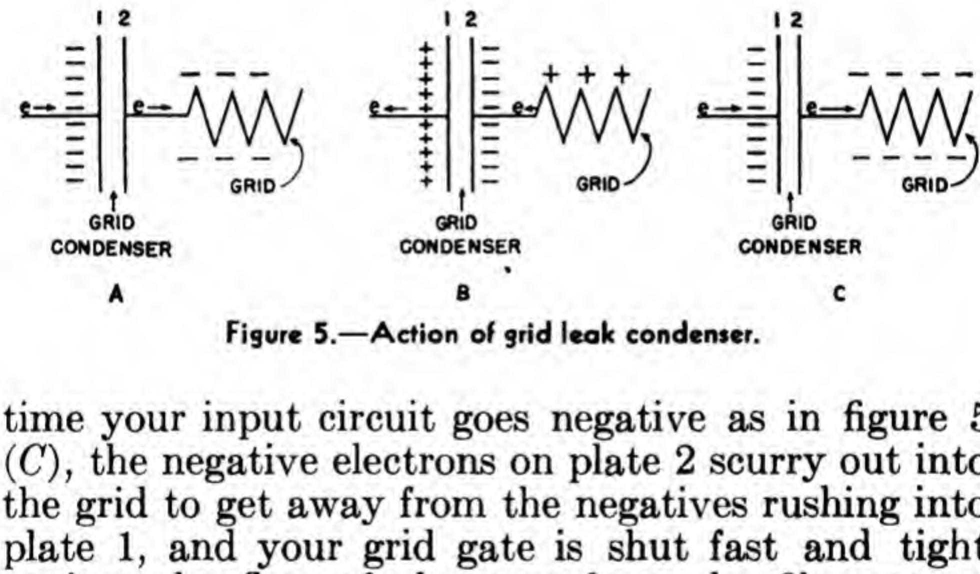


Figure 5.—Action of grid leak condenser.

time your input circuit goes negative as in figure 5 (*C*), the negative electrons on plate 2 scurry out into the grid to get away from the negatives rushing into plate 1, and your grid gate is shut fast and tight against the flow of electrons from the filament to the plate. Your condenser system WORKS, just as well as the "C" battery did, in fact.

But wait a minute! See what's happening? Every time the input changes from negative to positive, a few more negative electrons wander off the straight path from filament to plate and get mixed up with the other negative fellows on the condenser. This crowding could go on for a while, until you had the condenser so full of negative electrons that they'd hang out on the grid and clog up the

path from filament to plate and nobody could get through. The tube would stop working and your SOS would die right there between filament and plate, stopped by a gang of negative electrons.

Well, that's why you brought along a fixed resistor when you were setting out to build this circuit. You put a hard and rocky detour around the condenser so that a few of the negative electrons will find a way to escape from all the pushing and shoving on plate 2 and the grid. Now when your input circuit goes positive, a few of the negative electrons that are piled up around the condenser and grid can take the detour around the condenser and get out of the push. It's just a way of keeping down negative electrons on the grid to a small number that will help shut the gate when the input goes negative, but won't lean against the gate posts and impede traffic when the gate is open.

Ask the storekeeper for a GRID LEAK, which is a good name for it, since it allows excess electrons to leak off the grid. There are grid leaks of various resistance for various types of tubes. Grid leaks are rated in MEGOHMS, or millions of ohms resistance. A 2-megohm grid leak would appear as "2ω", written above the symbol for a resistor on the electrical diagram.

You've gotten rid of the "C" batteries. Now get those heavy, bulky "B's" out of the way. You've got a regular 110-volt electric light socket in your room, so use that socket as a source of power to replace the "B" batteries. But that socket gives out 110-volt, 60 cycle, a-c power, and you need something in the d-c line, without any cycles, and at about 45 volts. Forget the 110 a-c power? Nope, you can hammer it around, overhaul the stuff, and make it come out the way you need it.

DIODE or two-element vacuum tubes are the tubes that don't have a grid between filament and plate.

The diode tube takes in a. c. and puts out d. c. You can feed in your 110 volt a. c. and get out 110 volt d. c., with pulsations or beats in it. How to get the pulsations leveled out into a steady, smooth flow of d. c.?

You've probably carried water to the horses or the circus elephants. If you pump a bucket of water and then let the horse drink out of the bucket, he has to wait until you go back and fill the bucket

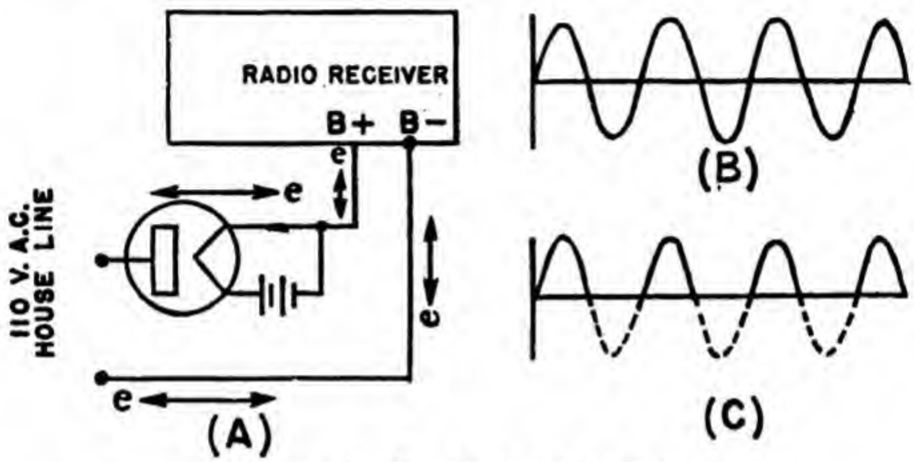


Figure 6.—The diode rectifier tube.

(a) The circuit.
(b) A-C wave before rectification.
(c) The lower half of the wave has been cut off. It's now pulsating d. c.

again, and bring it back to him. He's getting water in pulsations. But if you pour the bucket of water into the trough or a tub, he can go right on drinking while you go back for another bucketful. Then he gets a drink in a steady stream. Get the idea? Pour your buckets of current, or pulsations, into a tank or trough, and let them flow out through the pipe or output wire in a steady stream. No pulsations.

And that's just what you do when you put the pulsating d. c. from the diode or rectifier tube through a filter. The filter is an iron-core inductance coil, consisting of many turns of wire wrapped around a soft-iron core, and connected to a couple of condensers, as shown in figure 7.

The electrons of the pulsating d. c. are led from the output or plate of the rectifier tube to the inductance coil, which radio men call the FILTER CHOKE COIL. These electrons come along in small groups, a few at each pulsation, like people gathering at a closed gate in the railroad station. The high opposition of the filter choke coil acts as the gateman who makes the crowd wait at the station. But eventually the electrons, and the people, have gathered in such a

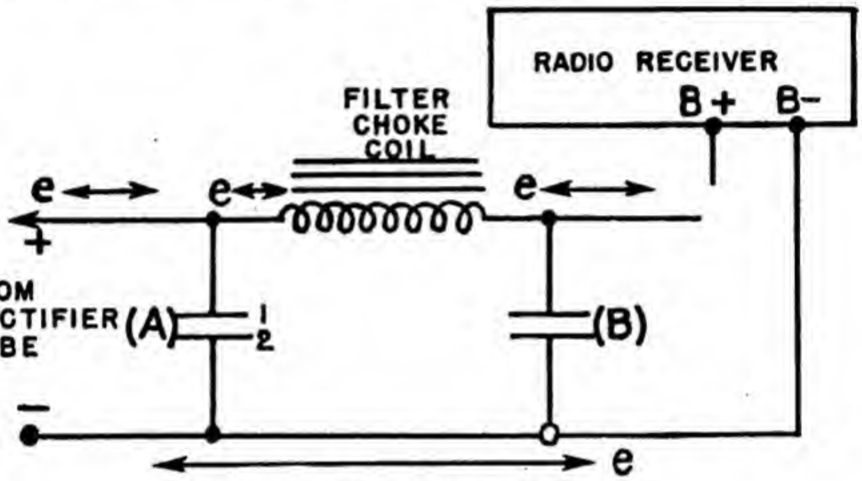


Figure 7.—Filter choke coil system.

crowd that they push their way past the filter choke coil and rush down the wire in a solid stream. That second condenser you put in the line at point *B*, figure 7, serves as a second storage tank to hold the steady rectified current until needed. And now you have converted your 110 a-c power over into 110 d-c filtered power and you can feed it to the plate of your tube if you need 110-volt power.

But you can't use 110-volt d-c power on the plate of your vacuum tube. In this case, you need 45-volt d-c power. Well, feed the 110-volt a. c. into a step-down transformer. You've put the proper number of turns of wire on the primary leg of your transformer to handle 110-volt power. And you've also wound the correct number of turns of wire on the secondary leg of your transformer to reduce the 110

a. c. to 45-volt a. c. You'll get the explanation of how this transformer works later in this book.

Anyway, for the present, all you need to know is that you can buy, build, or borrow a transformer that will step-down your 110-volt a-c power to 45-volt a-c power. This power is rectified and filtered before it is fed to the vacuum tube plate circuit to replace the "B" batteries.

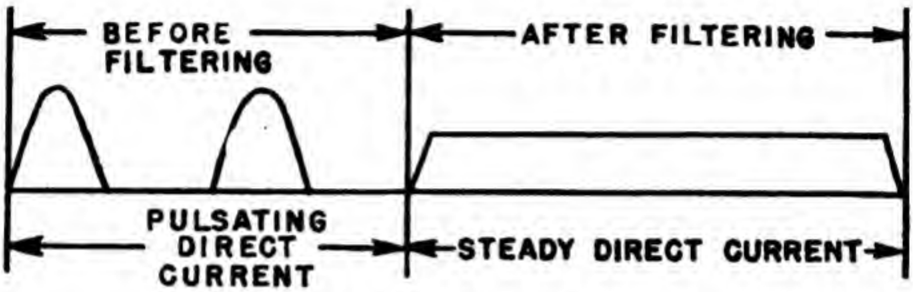


Figure 8.—Filtering pulsating direct current.

THE OSCILLATOR TUBE

You can also use the vacuum tube to generate an alternating current over a wide range of frequencies. A simple oscillator is diagrammed in figure 9. Here you see a vacuum tube circuit that differs from the amplifier you have already studied in two important respects.

First, no signal is fed into it from an antenna or a preceding stage. Second, the circuit is arranged so that current flowing in the plate circuit affects the grid circuit. In fact, you can see that in this particular circuit arrangement, the tuned circuit (*C–L*) is connected to both the plate and the grid by means of the condensers C_b and C_g.

Consider the instant when you connect your high d-c voltage to the points in the diagram labelled +B and $-B$. At this instant, electrons begin to flow from the filament to the plate, to the $+B$ terminal, to the $-B$ terminal, and then back to the filament. At

this same instant, the right-hand plate of condenser C_b is charged positive due to the fact that it is connected to the $+B$ terminal. This, in turn, causes the left plate of condenser C_b to be charged negative. Also, the lower plate of condenser C is charged negative as is the right plate of condenser C_g. This, in turn, causes a small negative charge to appear on the grid.

The effect of this negative charge on the grid is to REDUCE the flow of electrons from the filament to the

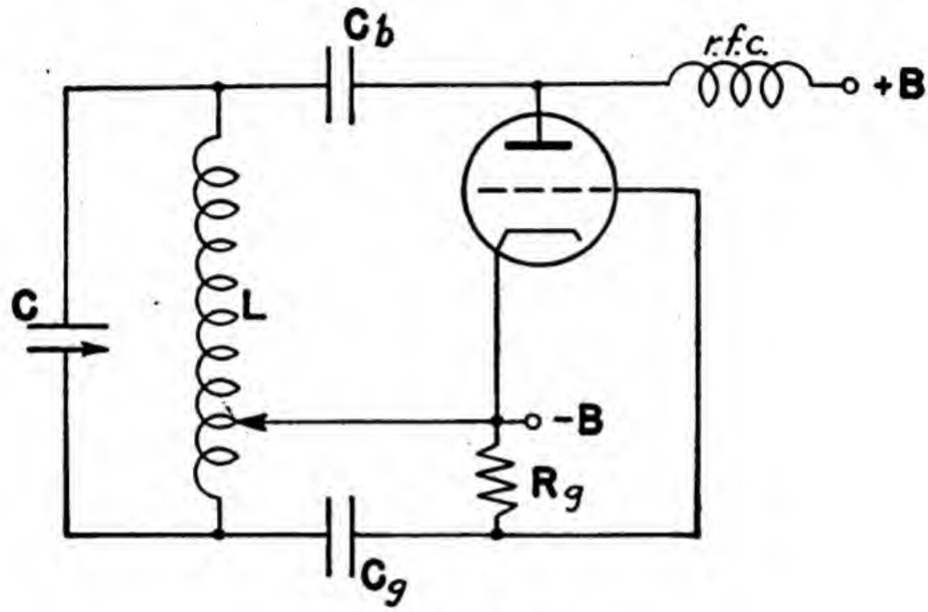


Figure 9.—Simple oscillator.

plate. When this happens the condensers start to discharge causing the grid to become LESS NEGATIVE. As the grid becomes less negative, MORE plate current flows and the condensers begin to charge again—the grid becomes charged slightly MORE NEGATIVE. And so on.

Thus, the grid alternately becomes MORE and then LESS negative. This is the same thing that happened to the grid when the tube was used as an amplifier—except that these alternations of voltage on the grid are caused by the plate current now instead of by a received signal.

However, the effect of these changes of grid charge upon the plate current is the same as before and the plate current keeps increasing and decreasing—following the pattern of a sine wave. The frequency of these alternations is determined by the size of L and C. The power to keep these alternations (or oscillations, as they are called) going is obtained from the plate current which, in turn, is driven by the "B" battery.

The coil labelled "v. f. c." keeps radio frequency currents out of the power supply and minimizes interference to other circuits which may be using the same power supply.

CHAPTER 2

MEASUREMENT INSTRUMENTS

D-C METERS

There'll be times when you'll want to check up on some circuits to see what's going on, how much current is flowing, what voltage you have, and so on. You may want to repair a circuit that's out of commission, or you may even be building a new circuit. On these jobs you can make good use of instruments to measure voltage, current, and resistance. And if you know how the various instruments work, you'll know why they give you the information you need. You'll also know how to check on their operation.

First you'll become acquainted with meters for measuring d. c.

GALVANOMETER

One of the simplest and most commonly used instruments is the MOVING-COIL GALVANOMETER. Look at figure 10. The galvanometer has a core made of soft iron. A coil of very fine wire is wound on an aluminum form around the core. The turns of wire

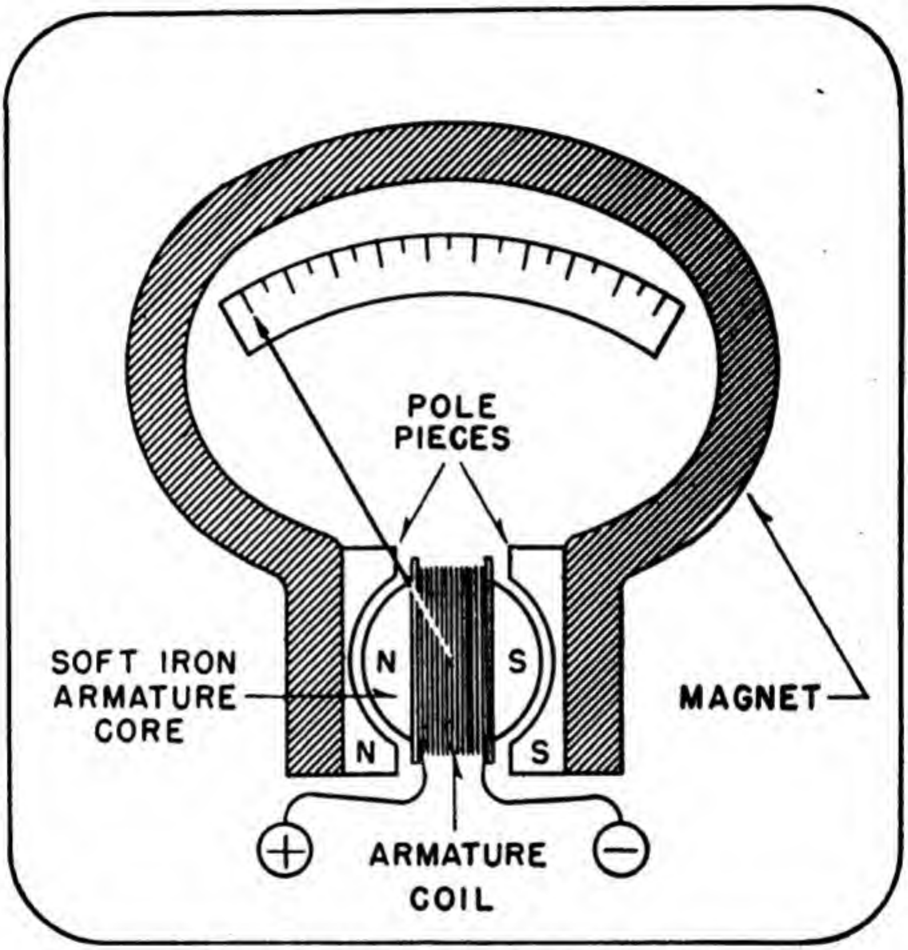


Figure 10.—Moving-coil galvanometer.

make up the armature coil. The core is rigidly fastened, but the coil form is mounted on a shaft seated in jewel bearings so as to be free to turn about the core. Rotation of the coil is controlled by a spring on each end of the shaft. These springs also act as current leads to the movable coil. The core and coil are placed between the poles of a U-shaped permanent magnet. One end of a pointer is fas-

tened to the armature shaft. As the shaft rotates, the other end of the pointer moves over a calibrated scale.

Current through the armature coil sets up a magnetic field. This coil field reacts with the magnetic flux of the permanent U-shaped magnet to rotate the coil with respect to the magnet. On this principle, current through the coil makes the coil turn a proportional amount. You can measure the travel of the pointer attached to the coil to determine the amount of current flowing through the meter.

The galvanometer is designed so that the maximum rotation of the armature is completed in less than a half-turn in a clockwise direction. The whole working assembly is enclosed in a glass-faced case that protects it from dust and air currents.

When you connect the galvanometer in the circuit, make sure that the leads carrying the current are attached to the correct binding posts. The posts are marked POSITIVE and NEGATIVE. The positive lead must be connected to the positive binding post, and the negative lead must be connected to the negative binding post. If this connection is reversed, the armature will start to rotate in the opposite direction and the meter may be damaged.

The simple galvanometer just described is designed to measure very small currents, usually no more than a few milliamperes. Often you must measure greater currents. Then you connect a metal bar, or SHUNT, across the galvanometer terminals.

Shunts have various carefully calibrated resistances. Generally, the shunt resistance is only a fraction of the galvanometer resistance. The current divides when it reaches the shunt. Part of the current flows through the galvanometer, and part through the shunt. Because current takes the path of least resistance, the greater portion of the current flows through the shunt.

The shunts must be carefully made and marked, or calibrated, to match the galvanometer. Unless you have a precise ratio of resistance between meter and shunt, you won't know accurately what the galvanometer readings really mean.

Suppose that 5 milliamperes of current is necessary to cause a full-scale deflection of the pointer. Also suppose that the resistance of the galvanometer armature itself is 99 ohms, and that you install a shunt which has a resistance value of 1 ohm. Because the resistance of the galvanometer is 99 times that of the shunt, 99/100ths of the current will flow through the shunt. The remaining 1/100th will flow through the galvanometer.

For example, your 5-milliampere galvanometer reads 4 milliamperes, indicating that 4 milliamperes must be flowing through the galvanometer. The resistance of the galvanometer is 99 times as great as the resistance of the shunt. Hence 99 times as much current must be flowing through the shunt itself. By simple multiplication of 99×4, you get a value of 396 milliamperes for the current flowing through the shunt. Add to this the 4 milliamperes flowing through the meter. A total of 400 milliamperes of current flows in the entire circuit.

AMMETER

As you already know, an AMMETER measures CURRENT, and must be connected to the circuit IN SERIES. When you insert the shunt, your galvanometer actually becomes an ammeter.

You can use the same galvanometer with shunts of various resistances. If you know the resistance of the galvanometer, you can calculate the resistance of the shunt necessary to extend the range of the meter to a desired point. Here's a formula you can use—

$$R = \frac{R_m}{(N-1)}$$

R is the resistance desired for the shunt. R_m is the resistance of the meter. N is the multiplication factor necessary to raise the range of the meter to the desired point.

FOR INSTANCE—Suppose the resistance, R_m, of the meter is 3 ohms, and the full-scale deflection represents 5 milliamperes. What do you do to find

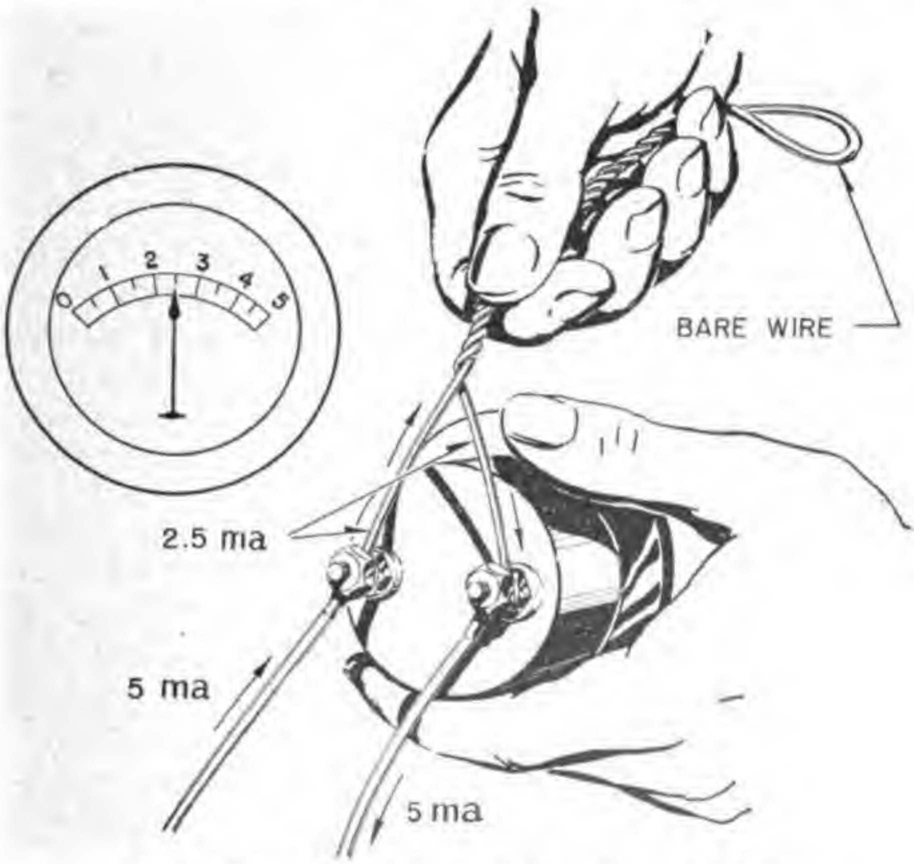


Figure 11.—Range-extension with twisted-wire shunt.

the value of the shunt necessary to extend the range of the meter to 100 milliamperes? First, divide 100 milliamperes by 5 milliamperes to get the multiplication factor, N, which turns out to be 20. So—

$$R=\frac{R_m}{(N-1)}=\frac{3}{(20-1)}=\frac{3}{19}=0.158 \text{ ohm.}$$

Most meters are supplied with built-in or internal shunts. How can you extend the range of such a

meter? To each terminal, you connect the ends of a bare wire. But first be sure you disconnect the meter from the current supply for safety-first. Then you twist the loop of wire together to form a shunt passage for the current across the meter, as in figure 11. To adjust the shunt resistance to the correct values, you ADD some twists or you partly UNTWIST the wire, depending on whether you need MORE or LESS resistance.

Suppose the original full-scale deflection of the meter represents 5 milliamperes, and suppose you must extend the range to 10 milliamperes. WITH THE CURRENT STEADY AT 5 MILLIAMPERES, you twist the wire together until the needle drops back to mid-scale deflection, or to read 2.5 milliamperes. Now a full-scale reading of the meter will represent 10 milliamperes.

USE OF VOLTMETER

You measure the potential difference existing between two points in a circuit by means of a voltmeter. See figure 12. As you know, voltage is a force which causes current to flow in a circuit. The amount of current flowing in a circuit is dependent on, and proportional to, the amount of voltage.

Suppose a voltmeter with an internal resistance of 1,000 ohms gives a full-scale deflection when 1 volt

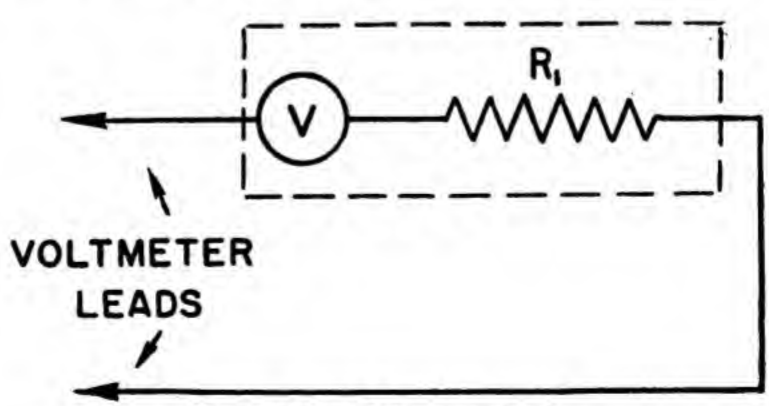


Figure 12.—Voltmeter circuit.

sets up a current of 1 milliampere. To place this instrument across a circuit where the voltage is greater than 1 volt, you must ADD SERIES RESISTANCE. Thus you limit to a safe value the amount of current flowing through the instrument. The resistor you add is called a MULTIPLIER, because it multiplies the range of the meter.

Again, suppose that the resistance of the moving coil plus the original series resistance is 1,000 ohms. If you increase the resistance of the meter to 2,000 ohms by adding 1,000 ohms in series, the pointer falls from FULL-SCALE reading to HALF-SCALE reading. Where 1 volt was formerly indicated by a full-scale reading, it is now indicated by a half-scale reading. You have, therefore, extended the range of the voltmeter from 1 volt to 2 volts.

You can use a simple formula to find the resistance necessary to extend the range of a voltmeter to a desired point—

$$R_x = \frac{R_m(V_2 - V_1)}{V_1}$$

R_x is the desired resistance. R_m is the meter resistance. V_2 is voltage to be measured, and V_1 is the voltage of the meter.

Here's a problem. The resistance R_m of your 3-volt meter is 1,000 ohms. You wish to increase the range of your meter to 25 volts ($V_2 = 25$). Then—

$$R_x = \frac{R_m(V_2 - V_1)}{V_1}$$

$$R_x = \frac{1,000\ (25-3)}{3} = 7,333 \text{ ohms}$$

So you need a 7,333-ohm resistor connected in series with the meter to increase the range of your voltmeter to 25 volts.

REMEMBER that in extending the range of a voltmeter, you must increase the amount of multiplier

resistance. Because the multiplier resistance remains constant for a given voltage range, the indication on the voltmeter increases with the voltage.

In measuring resistance, you may use the VOLTMETER-AMMETER method. The discussions in the following paragraphs will help you make the best connections using these meters.

To measure LOW values of resistance, connect the voltmeter DIRECTLY ACROSS THE RESISTANCE. If the load resistance is HIGH, connect the voltmeter ACROSS BOTH AMMETER AND LOAD. Another point—you should always use a voltmeter that has a very HIGH resistance. And here's WHY—

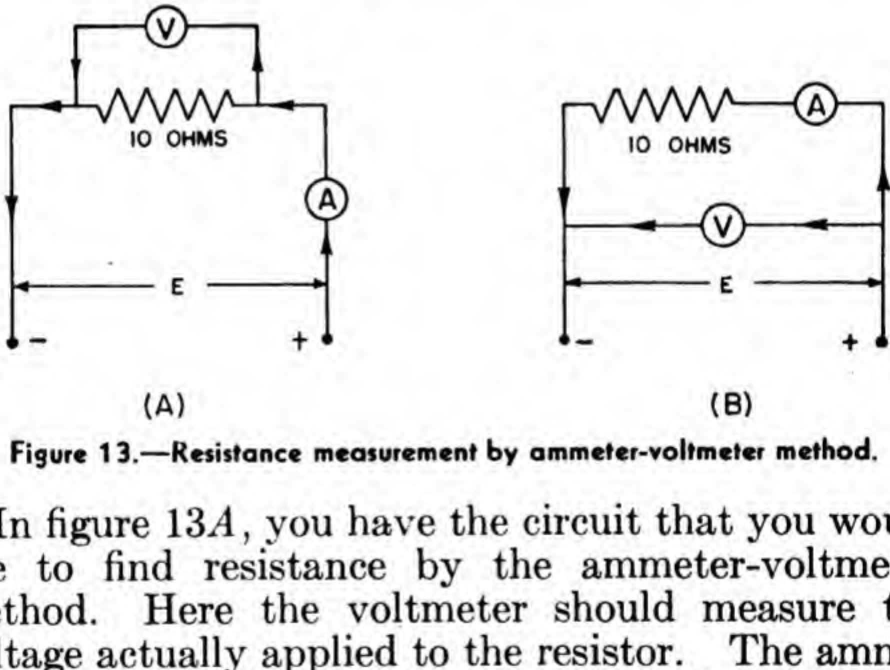


Figure 13.—Resistance measurement by ammeter-voltmeter method.

In figure 13*A*, you have the circuit that you would use to find resistance by the ammeter-voltmeter method. Here the voltmeter should measure the voltage actually applied to the resistor. The ammeter should measure the current through it. You can easily see that the voltmeter does measure voltage through the resistor. But the ammeter is not measuring the current through the resistor alone. It measures the current through BOTH the resistor and the voltmeter. If the current through the voltmeter is large, you introduce a considerable error in substituting these values in the formula for Ohm's Law.

Suppose you want to measure a resistance which

you already know is 10 ohms. For convenience, you apply a voltage to the circuit so that the voltmeter V reads 10 volts. Then the current I through the 10-ohm resistor would be—

$$I_R=\frac{E_R}{R_R}=\frac{10}{10}=1 \text{ ampere}$$

But your voltmeter has an internal resistance of 100 ohms. So, the current through the voltmeter is—

$$I_V=\frac{E_V}{R_V}=\frac{10}{100}=0.1 \text{ ampere}$$

Now if you put these readings in the formula for total circuit resistance, you get—

$$R=\frac{E}{I}=\frac{E}{I_R+I_V}=\frac{10}{1+0.1}=\frac{10}{1.1}=9.09 \text{ ohms}$$

and your ammeter reading would be 1.1 amperes.

But you already know that $R=10$ ohms, so you have an error of $10-9.09$ or 0.91 ohm, all because you have connected your ammeter in figure 13*A* so that it measures current through the resistor AND the voltmeter. You are using a false reading for current through the resistor alone.

Now suppose the resistance of the voltmeter happened to be 10,000 ohms, instead of 100 ohms. Then—

$$I_R \text{ would still be } I_R=\frac{E_R}{R_R}=\frac{10}{10}=1 \text{ ampere.}$$

BUT—

$$I_V \text{ now is } I_V=\frac{E_V}{R_V}=\frac{10}{10{,}000}=0.001 \text{ ampere.}$$

AND—

$$I_V+I_R=1+0.001=1.001 \text{ amps.}$$

THEN, in this case the calculated resistance of R is—

$$R=\frac{E}{I}=\frac{10}{1.001}=9.99 \text{ ohms}$$

But you know that R actually equals 10 ohms, so your calculated error is $10-9.99$ or 0.01 ohm. You can see now that in order to get an accurate reading for the circuit connection of figure 13*A*, you ought to use a voltmeter with a HIGH internal resistance as compared to the resistance to be tested.

If you know the resistance of a voltmeter, you can figure the voltmeter current for any voltage reading. Then you subtract this current from the ammeter reading to determine the ACTUAL CURRENT through the resistor. If you are to get the correct resistance value of the resistor itself, you must substitute this actual value of resistor current in your formula,

$$R=\frac{E}{I}.$$

In figure 13*B*, you have a slight variation from the original circuit diagram. The ammeter is now connected between the voltmeter and the resistor. Now the current taken by the voltmeter is of no importance. With this particular arrangement, the ammeter reads the TRUE current through the resistor. But the voltmeter is not measuring the voltage applied to the resistor. The voltmeter measures the voltage across the series combination of ammeter AND resistor.

Suppose the ammeter has a resistance of 1 ohm, and the resistor to be measured has a resistance of 10 ohms. If the applied voltage causes a current of 1 ampere to flow, the ACTUAL voltage applied to the resistor is—

$$E=I_R R_R=1\times 10=10 \text{ volts.}$$

The voltmeter will not indicate 10 volts, because the drop across the ammeter is included. The drop is $E=IR=1\times 1=1$ volt. The total voltage reading is 11 volts. If you put these meter readings in the

formula, $R=\frac{E}{I}=\frac{11}{1}=11$, you get a value of 11 ohms for the resistance. The error is $11-10$ or 1 ohm.

If the resistance of the ammeter is only 0.001 ohm, the resistance of ammeter AND resistor becomes $10+0.001=10.001$ ohms, and the voltmeter reading would become $E=IR=1\times 10.001=10.001$ volts. The resistance of the resistor is calculated as $R=\frac{E}{I}=\frac{10.001}{1}=10.001$ ohms. Here the error would be only $10.001-10$ or 0.001 ohm. So the error is large only if the ammeter resistance is about equal to the load resistance. And the lower the resistance of the ammeter, the lower is the error.

OHMMETER

You can convert an ammeter into an OHMMETER. In figure 14*A*, you have a 3-volt battery connected to a milliammeter with a full-scale reading of 5 milliamperes. The current-limiting resistor R has a value such that exactly five milliamperes flow in the circuit. This resistance is found by a simple application of Ohm's Law. Since $E=3$ volts, and $I=.005$ amperes, the proper limiting resistance is—

$$R=\frac{E}{I}=\frac{3}{0.005}=600 \text{ ohms.}$$

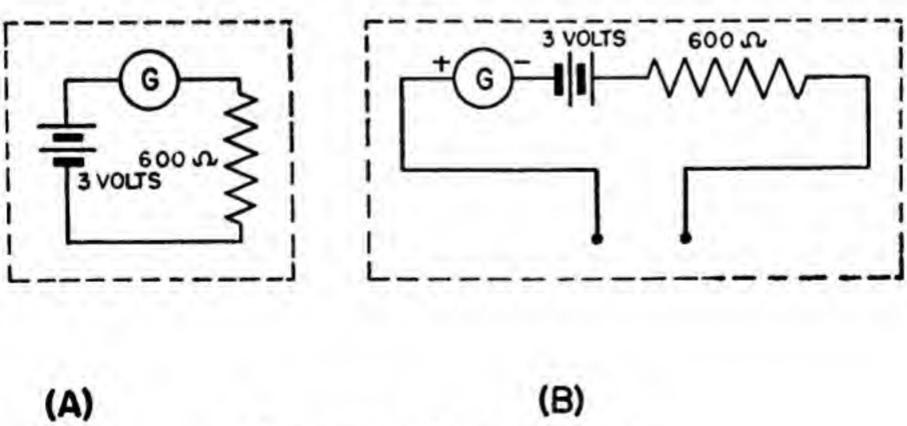


Figure 14.—Ohmmeter circuit.

In figure 14*B*, the circuit has been equipped with two binding posts. With no connection across the posts, the current will be zero. If you close the circuit at these posts through practically zero resistance, the meter will return to its full-scale reading of 5 milliamperes. If you connect a second 600-ohm resistor between the binding terminals, the total resistance is now 1,200 ohms. The meter will drop to one-half its former reading, or to read 2.5 millamperes, since $I=\frac{E}{R}=\frac{3}{1{,}200}=0.0025\text{ a}=2.5\text{ ma}$.

If the battery voltage and the limiting resistor (R) remain constant, the pointer will always move to 2.5 milliamperes whenever you put 600 ohms across the posts. You can now mark this point on the scale of the meter "600 ohms." You have converted the milliammeter into an ohmmeter, capable of reading one value of resistance—600 ohms.

Now put a 2,400-ohm resistor across the binding posts. This plus the original 600 ohms resistance of the meter equals 3,000 ohms total. The pointer will drop to 1 milliampere on the scale, since $I=\frac{E}{R}=\frac{3}{3{,}000}=0.001$ ampere, or 1 milliampere. Again if the battery voltage and the limiting resistor remain constant, the meter will always read 1 milliampere when you put a resistance of 2,400 ohms across the posts. So, you can mark "2,400 ohms" alongside the 1-milliampere point on the meter scale. The meter instrument is now capable of measuring 600 ohms and 2,400 ohms.

In a similar manner, by placing other known resistances across the binding posts, you can calibrate the instrument to measure resistance values over the entire range of the meter scale.

MEASURE RESISTANCE WITH WHEATSTONE BRIDGE

A WHEATSTONE BRIDGE is an instrument used for making accurate resistance measurements. Figure 15 shows the schematic diagram of a typical Wheatstone bridge. It consists essentially of THREE RESISTORS, A SENSITIVE GALVANOMETER, AND A POWER SUPPLY. Two resistors—R_1 and R_2—are fixed resistors of known values, the third—R_3—is a variable

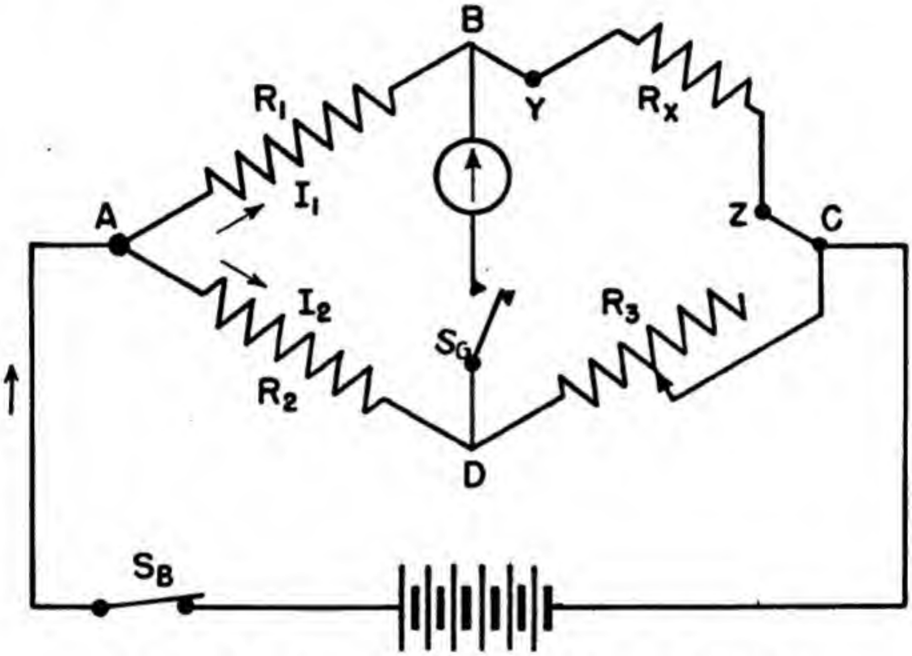


Figure 15.—Schematic diagram, Wheatstone bridge.

resistor with the necessary calibration arrangement to read the resistance value at any setting. You connect the UNKNOWN resistor—Rx—across the binding posts at Y and Z.

Connect the battery at points A and C. When you close switch S_B current flows in the direction of the arrows. You get a voltage drop across all four resistors in the circuit. Ordinarily, R_1 is equal to R_2. Next, adjust variable resistance R_3 so that the galvanometer registers ZERO when the switch S_G is closed. At this adjustment, R_3 is equal to R_x in

resistance. By reading the resistance of R_3, you know the resistance of R_x.

And here's why and how! Point B will be at the same electrical potential as point D if the variable resistance R_3 is equal to R_x. Under this condition, NO current flows through the galvanometer when the galvanometer switch is depressed. If R_x is not equal to R_3, then B and D are not at the same potential, and current WILL flow through the galvanometer when the switch is closed. But you will adjust R_3 until no current flow is obtained through the meter. Then $R_3 = R_x$.

But R_1 and R_2 need not always be equal in resistance.

To get an accurate reading, you should select R_1 approximately equal to what you think R_x will be. In the most accurate types of Wheatstone bridge, the resistance of R_1 is known, but can be varied in steps. The following formulas show you how to find the unknown resistance of R_x for any values of R_1, R_2, R_3.

The voltage drop across $AB = I_1R_1$

$$AD = I_2R_2$$

$$BC = I_1R_x$$

$$DC = I_2R_3$$

ALSO—

$$I_1R_1 = I_2R_2$$

$$I_1R_x = I_2R_3$$

If equals are divided by equals, the results are equal.

THEREFORE—

$$\frac{I_1R_1}{I_1R_x} = \frac{I_2R_2}{I_2R_3}$$

$$\frac{R_1}{R_x} = \frac{R_2}{R_3}$$

$$R_x = \frac{R_1R_3}{R_2}$$

When using the Wheatstone bridge, you must be sure that ALL CONTACT POINTS ARE CLEAN so that you won't be putting additional resistance into the circuit. Dirty points will give you false readings.

WHAT'S A MEGGER?

When you run into more than 10 megohms resistance, the ohmmeter is not a satisfactory meter. This is because the voltage used in the ohmmeter is very low. A MEGGER overcomes this disadvantage.

The megger is a first cousin to the ohmmeter. The megger scale reads measured values of resistance directly. The megger has two main elements, a magneto d-c generator to supply current for making the measurement, and an ohmmeter which measures the value of the resistance you are testing. You turn the armature of the generator by a hand-crank, generator speed being stepped-up by gears. The normal output voltage of the generator is about 500 volts. A schematic diagram of the megger is shown in figure 16.

The indicating element has two coils, which are mounted on the same shaft, but are set at right

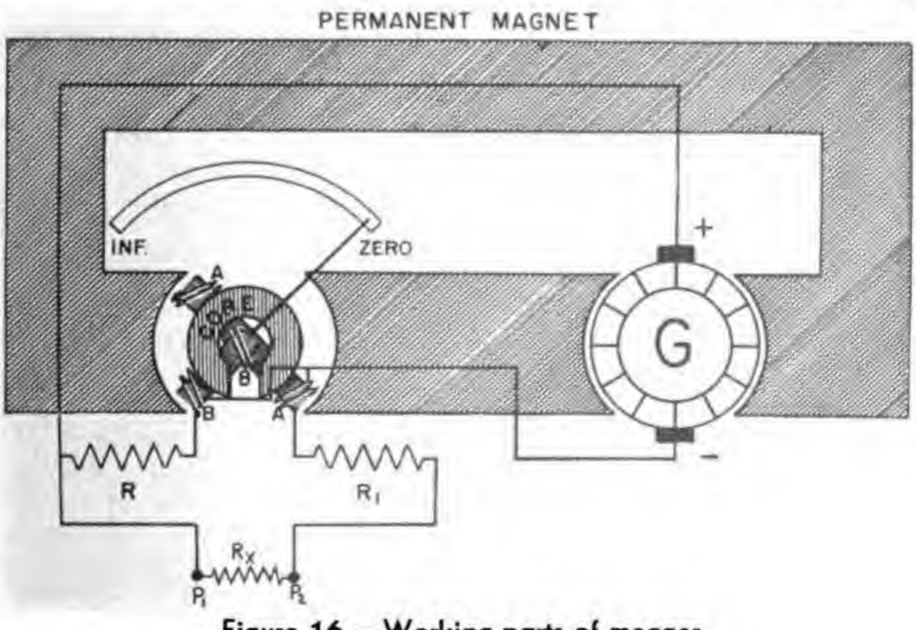


Figure 16.—Working parts of megger.

angles to each other. You will see that coil A is of the same type used in most d-c voltmeters. Coil B is smaller and is mounted so that at some positions it encircles a part of the core, which is C-shaped. You feed current to both coils by means of flexible connections that do not hinder the rotation of the element.

Coil A is the current coil. Hook one terminal of this coil to the negative brush of the generator and put this coil in series with resistance R_1 to the external terminal P_2. Lead the other external terminal P_1 to the positive brush of the generator. When you connect an unknown resistance between the external terminals, current flows from the generator through coil A, resistance R_1, and the unknown external resistance R_x. Resistance R_1 has enough resistance so that even if the line terminals are short-circuited, the current coil will not be damaged.

Coil B is the potential coil. You connect this coil across the armature of the generator through a suitable resistance R. If the line terminals are left open-circuited or if the external resistance R_x is of enormous value, no current will flow in coil A, and coil B alone will move the pointer. Coil B will take a position opposite the gap in the C-shaped core and the pointer will indicate INF (infinity). If, however, you put a resistance R_x between the line terminals, current will flow in coil A. The corresponding torque developed will move the indicator away from the INF position into a field of gradually increasing strength until equilibrium is established between the field torques of coils A and B. You can calibrate the scale in terms of resistance. Since changes of generator voltage affect both coils in the same proportion, variations in the speed of the hand-cranked generator will not affect the readings of the megger.

The 500-VOLT PORTABLE MEGGER is one you use most widely in aircraft work. It has many uses, and

you will learn by experience when and where to use this instrument. Here are some of its uses—

To test insulation resistance of generator, and dynamotor field coils and connection blocks.

To test for high-resistance grounds, or leakage on antenna, transmitter, and receiver insulators.

To test for high-resistance grounds on radio direction-finder loops.

To test capacitors whose peak voltages are not below the output voltage of the megger.

To test for high-resistance grounds on ignition harness. This is not a very satisfactory method of testing ignition harness, since the voltage on the megger is not high enough for a real test. However, it can be used if you do not have an ignition harness tester, which supplies a much higher voltage.

A-C METERS

A-c meters are similar in one respect to d-c meters. They are nearly all current-measuring devices. However, the reversals of the a. c. prevent you from using the moving coil-permanent magnet principle. Therefore, you will have to use some method by which force in only one direction is obtained, in spite of the reversal in current. You can do this with five main types of a-c meters. These are the DYNAMOMETER, the HOT-WIRE, the IRON-VANE, the THERMOCOUPLE, and the RECTIFIER-TYPE meters.

DYNAMOMETER

In the DYNAMOMETER, you have fixed field-coils and a movable coil to which a pointer is attached. A light spring is attached to this moving-coil to retard its movement.

Here's how the dynamometer works. Look at its action on the first half of the a-c cycle. You've

wound your fixed and movable coils so that the magnetic fields have the polarities shown in figure 17. The attraction of the magnetic forces tends to turn the movable coil in the direction indicated, since its field tries to line up with the fields of the fixed coils. This moves the pointer up the scale to the right. The distance it moves is determined by the coil spring attached to the pointer shaft. When the tension on the spring becomes equal to the pull of the magnetic fields, the pointer will come to rest.

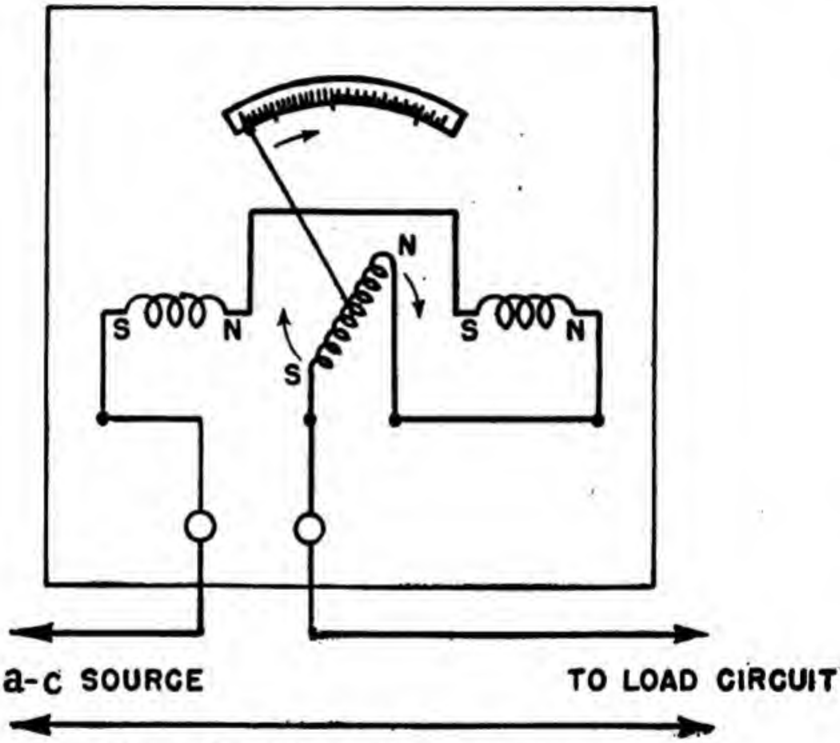


Figure 17.—Dynamometer as an ammeter.

This goes for only one-half cycle. However, you can see that when the current reverses, the polarity of all coils will reverse. When this occurs, the same amount of force is still exerted to turn the movable coil. The direction of rotation is the same as before—to the right or clockwise. So, your meter will always read in a positive direction. The readings are approximately proportional to the square of the current.

Use the dynamometer as a low-current meter or as a laboratory ammeter for small currents. The leads to carry heavy current will be too heavy to make it practical to use the meter for high-current readings.

You can use the dynamometer as a voltmeter by connecting a current-limiting resistor R_1 in series with the internal circuit, as in figure 18. The principle is the same for a-c instruments as for d-c instruments.

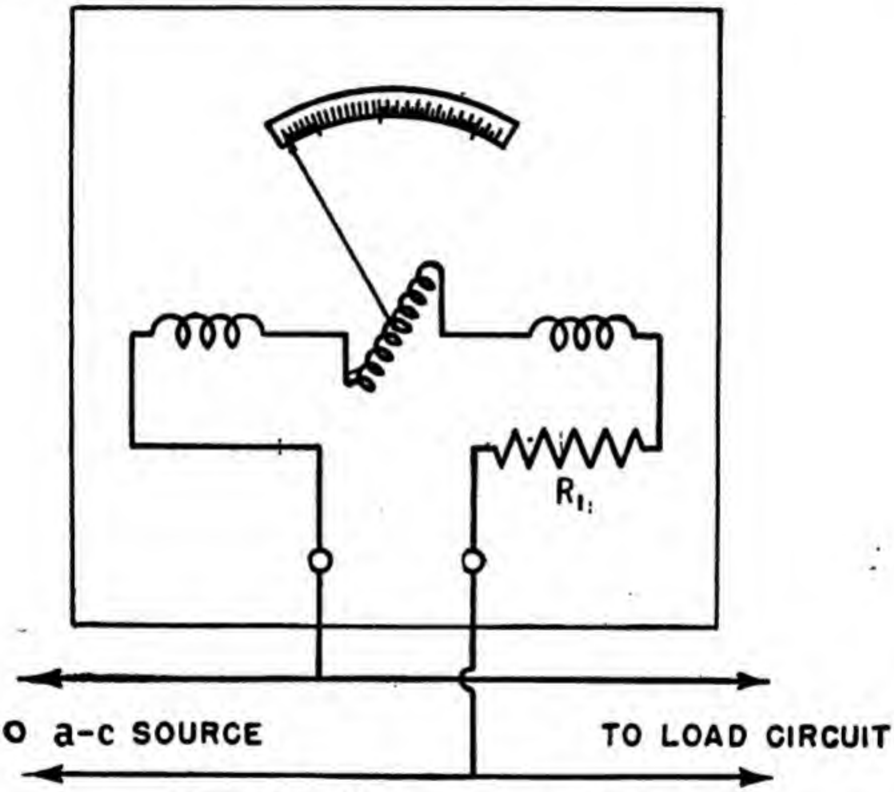


Figure 18.—Dynamometer as voltmeter.

HOT-WIRE AMMETER

You'll use the HOT-WIRE AMMETER to measure SMALL ALTERNATING CURRENTS OF RADIO-FREQUENCY. This alternating current travels through a fine wire stretched horizontally between points A and B in figure 19. Another wire is attached to point C on the horizontal wire and is fastened at point D. A fine thread attached to point E of this second wire is also

attached to the indicator at point *F* and tied to a small spring at point *G*. As the current passes over the wire *AB*, the resistance encountered causes the current to heat and expand the wire. This slight expansion lengthens the wire. The spring *G* deflects the pointer. The heating effect is proportional to the square of the current through the wire. Hence the calibrated spaces on the scale of a hot-wire ammeter are not equally spaced, but increase as the square increases.

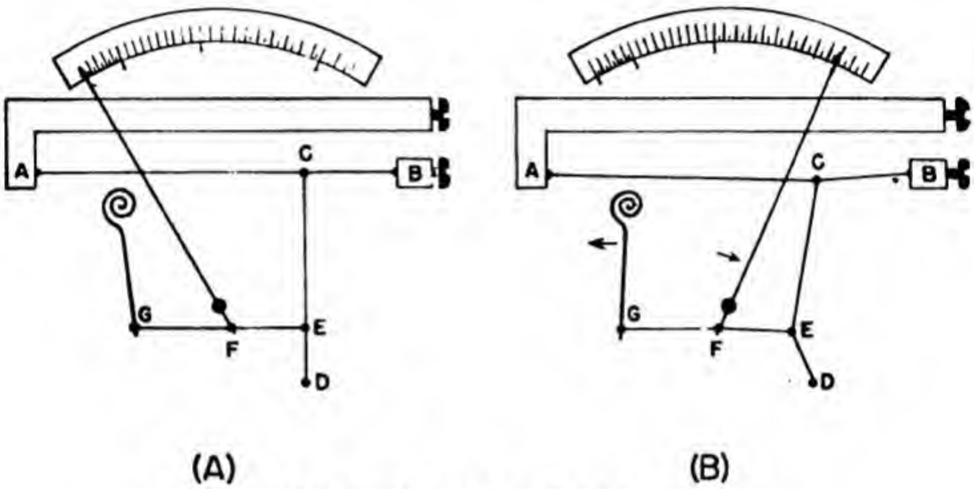


Figure 19.—Hot-wire ammeter.

Figure 19*B* shows relative positions of the wires and pointer when the meter is in operation.

IRON-VANE METER

You can also measure a. c. with the IRON-VANE METER. Look at figure 20. This meter has two soft-iron magnetized pieces or vanes mounted inside a coil. One of these vanes is fixed, while the other is free to move. You attach a shaft and pointer to the moving vane. As the current flows through the coil of wire, the two vanes become magnetized.

Since they are magnetized in the same way—with like poles at the same ends—these vanes try to REPEL each other. The free vane moves away from

the fixed vane. This turns the shaft and moves the indicator across the calibrated scale. Even though the direction of the current changes on each half-cycle, the two vanes are always magnetized alike, and so continue to repel each other. Reversals in current have no effect on the indication of the pointer. Since the amount of magnetism developed in the two vanes is directly dependent on the amount of current passing

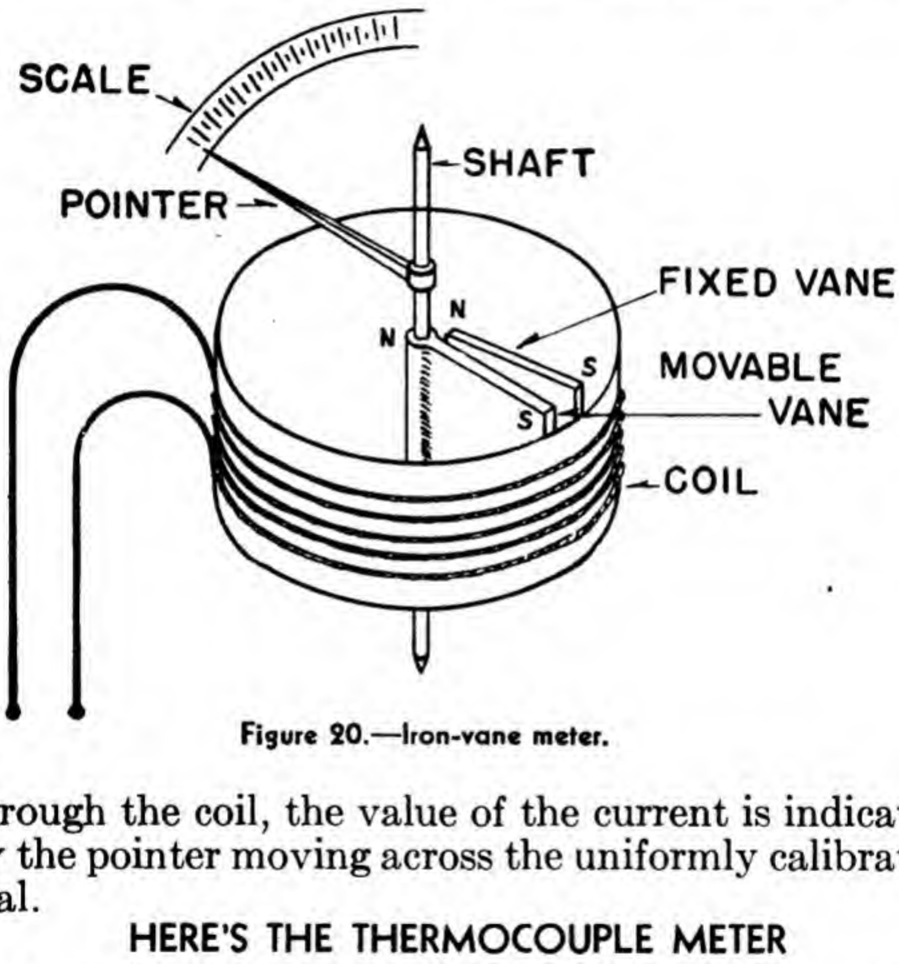


Figure 20.—Iron-vane meter.

through the coil, the value of the current is indicated by the pointer moving across the uniformly calibrated dial.

HERE'S THE THERMOCOUPLE METER

An instrument that you can use in measuring a. c., or radio frequency, is the THERMOCOUPLE AMMETER, figure 21. Here's how it works. When two dissimilar metals are connected at one end, and heat is applied to the CONNECTED ends, a d-c electromotive force, or d-c voltage, is developed across the OPEN ends of the two dissimilar metals.

This voltage is directly proportional to the temperature of the wires in the heated junction. The generation of d-c voltage by heating the junction of these two dissimilar metals is called THERMOELECTRIC ACTION. This device is called a THERMOCOUPLE.

Any two dissimilar metals will produce a voltage across the open ends, when you heat their junction.

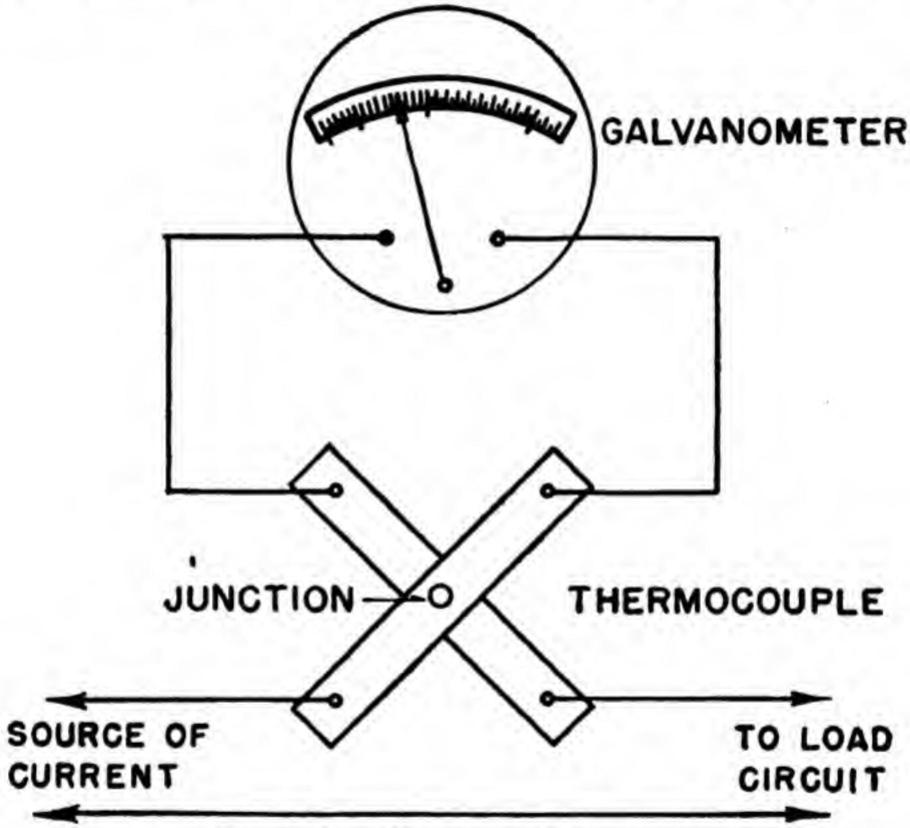


Figure 21.—Thermocouple ammeter.

But two wires, one an alloy of bismuth and the other an alloy of antimony, will produce the greatest possible voltage per degree of temperature difference. An electric current passing through a wire or conductor will produce heat in that wire in proportion to the square of the current. Therefore, if you pass a current through the junction of a thermocouple, heat will be generated in the wires, and a voltage will be produced at the open ends.

If you connect a calibrated galvanometer to the free ends of the thermocouple wires, you can measure this generated voltage. The direction of the current in the thermocouple has no effect on the heating of the wire. Therefore, you can use the thermocouple to measure either d. c. or a. c.

Frequently, you'll have to measure a. c. without stealing any more power from the circuit than is

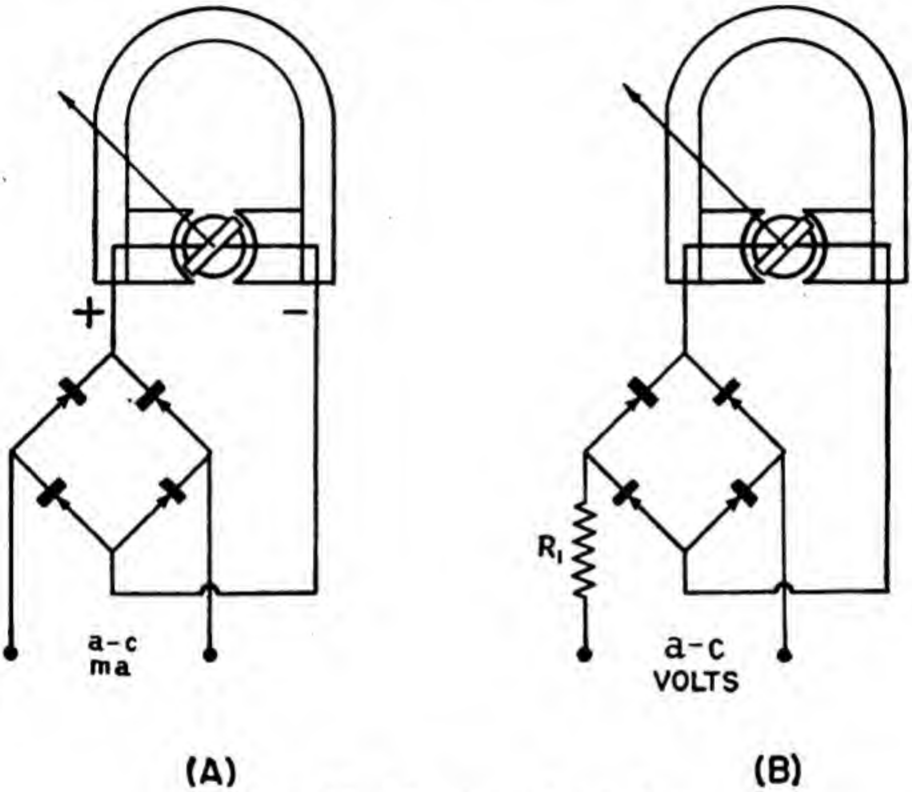


Figure 22.—Copper-oxide rectifier.

absolutely necessary. You can't use the low-power d-c meters on a. c., and a-c meters of the moving-vane and dynamometer types use up a lot of juice. The solution—rectify your a. c. into d. c. and measure it with d-c instruments.

Run your a-c power through a COPPER-OXIDE RECTIFIER, figure 22, and you come out with d-c power, ready to measure on a low-power, sensitive d-c moving coil meter. The d-c output of the rectifier is

proportional to the a-c input. With the d-c output of the rectifier applied to the d-c meter, you can calibrate the meter to read a-c voltage or current.

The copper-oxide rectifier offers a high resistance to the flow of current in one direction, and a low resistance to the flow in the opposite direction. You get a pulsating d-c output which you can feed to the meter.

The copper-oxide rectifier usually consists of a junction between two dissimilar substances, generally a metal and a crystalline metallic salt which will conduct electricity. This combination offers a comparatively low resistance to the flow of current in one direction. That is to say, there is a high resistance from the crystalline metallic salt to the metal, and a low resistance from the metal to the crystalline metallic salt.

You cannot use the copper-oxide rectifier type meter for the measurement of high-frequency a. c. The high-frequency currents passing through the rectifier generate too much heat. This heat lowers the accuracy of the meter. You will note in figure 22*A*, the connection of the line to the rectifier for measurement of current. For the measurement of a-c voltage, insert a resistor R_1 in series with one leg of the line. You can increase the range of the copper-oxide rectifier voltmeter by the use of this multiplier resistor. This is shown in figure 22*B*.

For the measurement of high frequency a-c currents and voltages of low values, you can use a CRYSTAL RECTIFIER type of meter. The operation of this crystal rectifier meter is practically the same as the copper-oxide rectifier. The crystal allows current to pass more easily in one direction than it does in the other. Its application is limited, however, to the measurement of very small currents and voltages.

CHAPTER 3

AIRCRAFT ELECTRICAL INSTRUMENTS

PANEL INSTRUMENTS

You'll find a number of ELECTRICAL INSTRUMENTS on the instrument panel of any airplane. They indicate to the pilot and the flight engineer whether the engine temperature is correct, whether the landing wheels are up or down, how many gallons of gasoline there are in the tanks, and other important information.

You'll need to know how to keep these electrical instruments in good working order. So you must know how they work.

TEMPERATURE INDICATORS

Temperature indicators let the pilot know at all times what the temperature is at the engine cylinder heads, what the engine-oil temperature is, the temperature of the air he's flying through, and certain other temperatures. These temperatures tell him if his engines are working properly, if he should adjust fuel mixtures, if he should start his de-icers, and so on.

Most, but not all, electrical instruments use the principle of the WHEATSTONE BRIDGE. Look at figure 23 for a diagram of how you use this Wheatstone Bridge in temperature indicators.

There are THREE main parts to this indicator—the BULB or heat-sensitive element which extends out into the air or is immersed in the engine oil; the LEAD WIRES which lead from the bulb to the indicator;

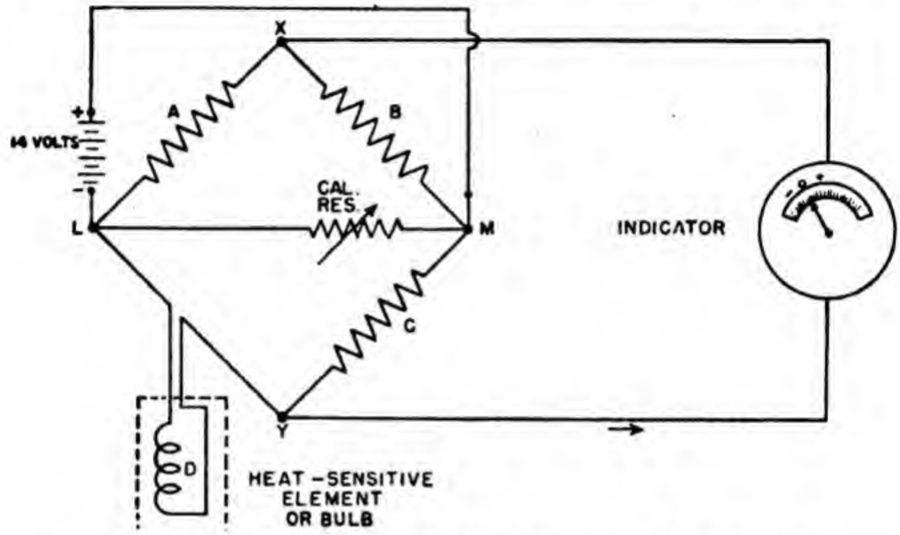


Figure 23.—Wheatstone bridge temperature indicator.

and the INDICATOR or meter that is set in the instrument panel.

Here's how the whole thing works.

A Wheatstone bridge is made up of four resistors having equal resistance, usually 100 ohms at 0° C. You connect a battery, usually 12 or 24 volts in aircraft, to points L and M of the bridge. At 0° C and with the bridge adjusted through a rheostat, you will make X and Y have equal potentials—no current will flow. A meter between X and Y would read zero.

Three of the resistors are fastened into the circuit by mounting them as spools of wire on the back of the indicator on the instrument panel. The fourth resistor is in the bulb, which is subjected to the temperature of the cylinder head, the oil, or the air.

When the temperature of the resistor in the bulb rises, the resistance of the resistor increases in proportion to the temperature. This change in resistance unbalances the Wheatstone bridge and causes a current to flow in the circuit through points *X*, *Y*, and the indicator. The indicator measures current, but the indicator dial can be calibrated to show degrees of temperature.

Likewise, if the temperature at the bulb drops below 0° C, the resistance of the bulb element is lowered, current flows through the meter circuit in the opposite direction, giving a negative reading, and measuring degrees below 0° C.

The indicator on the instrument panel is usually a d'Arsonval galvanometer. This unit is shielded by a soft iron case to prevent the magnets in the galvanometer from interfering with the aircraft compass.

The leads that connect the indicator to the bulb are usually No. 16 B & S gage copper wire, covered with a metal shield to prevent static in the aircraft radio.

The resistor in the bulb is made up of a number of turns of nickel wire on an aluminum tube, and covered with a Monel metal case. Enough turns of wire are used to give 100 ohms resistance at 0° C.

The temperature indicator will usually be calibrated when you receive it, so no further calibration should be necessary. However, you should check it regularly, after every 50 hours of use, to see if it reads correctly. Simply disconnect the battery connections to the indicator, and see if the meter needle moves to zero position (0° C). The bulb needs no attention, if it is not exposed to excessive temperatures (300° C or more). And the meter should require no repairs. If the meter goes bad, you should replace it, and return the damaged meter to an instrument shop.

CYLINDER TEMPERATURE INDICATORS

The cylinder temperature indicator in figure 24 tells the pilot the temperature of air-cooled engine cylinder heads. It gives him information on engine load and performance to enable him to adjust his engine controls to the most efficient range.

This instrument makes use of the THERMOCOUPLE principle, When two dissimilar metal wires are connected together at one end and the joint is heated, you generate a voltage at the opposite or open ends of

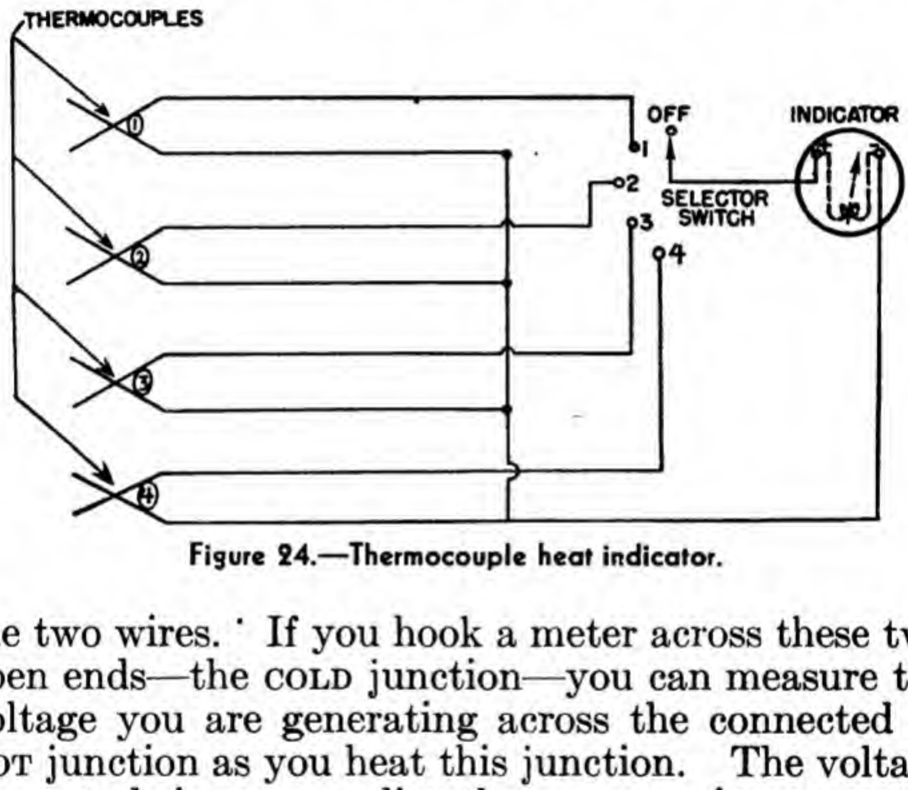


Figure 24.—Thermocouple heat indicator.

the two wires. If you hook a meter across these two open ends—the COLD junction—you can measure the voltage you are generating across the connected or HOT junction as you heat this junction. The voltage generated increases directly as you increase the amount of heat you apply to the hot junction. You can calibrate the voltmeter to read degrees of temperature instead of volts.

Now couple two different metal wires together—the Navy usually uses a COPPER and a CONSTANTAN wire, constantan being an alloy of copper and nickel. (The Army uses IRON and CONSTANTAN). Fasten this hot junction to a copper gasket ring that will

fit under a spark plug like an ordinary spark plug gasket. Lead the two wires from the cylinder head to a voltmeter on the instrument panel, and the pilot will be able to tell the temperature of that cylinder head of his engine. You don't need any battery in the circuit, since the voltage is generated by heating the hot junction of the two metal wires.

But the voltage generated across the cold junction is dependent upon the difference in temperature between the hot and the cold junctions. So you have to find a way to keep the voltmeter properly adjusted to changes in the cold junction temperature. This is done by putting a bimetallic spring in the voltmeter to adjust the tension on the indicator needle spring as the temperature of the indicator changes—for example, when a plane takes off from a hot tropical airport and climbs into the cold upper air.

You should check the accuracy of this thermo-couple occasionally by disconnecting one of the leads from the cold junction to the indicator. The meter should then indicate the temperature of the cockpit. This reading is checked with an ordinary mercury thermometer which you hang in the cockpit beside the indicator. An adjusting screw on the indicator enables you to adjust the needle to agree with the mercury thermometer.

NEVER LENGTHEN or SHORTEN the copper-constantan leads from the hot junction to the indicator. Their resistance determines the calibration of the indicator. If you change their lengths, you change their resistance, and upset the accuracy of the indicator. Always be sure to use a constantan lead from the constantan couple of the thermo-couple to the instrument, and a copper lead from the copper couple.

Perhaps you need to read the cylinder-head temperature of all four engines on a plane. One

indicator connected through a 4-station selector switch to a thermocouple on each engine will do the job.

ELECTRICAL TACHOMETER

The speed in rpm of an aircraft engine is indicated by a TACHOMETER (pronounced "ta-KOM-e-ter") mounted on the instrument panel.

The simplest form of ELECTRICAL TACHOMETER is based on the fact that the voltage induced in a permanent-field generator is proportional to the speed or rpm of the generator. If the generator is

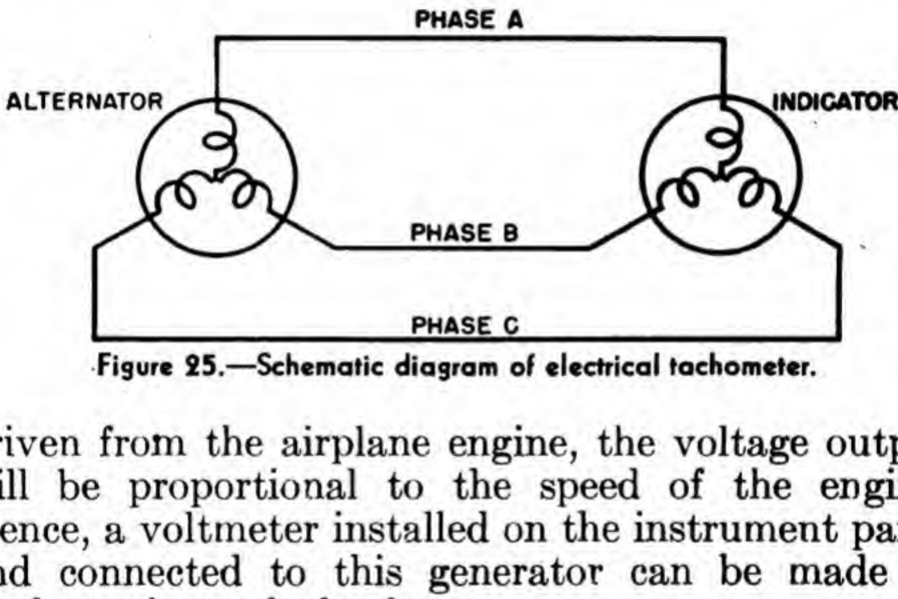


Figure 25.—Schematic diagram of electrical tachometer.

driven from the airplane engine, the voltage output will be proportional to the speed of the engine. Hence, a voltmeter installed on the instrument panel and connected to this generator can be made to read rpm instead of voltage.

In recent installations an a-c three-phase generator is used. A three-wire line carries the power from this a-c generator to a synchronous motor in the indicator unit mounted on the instrument panel. The indicator in this unit, however, is NOT a simple voltmeter, but a MAGNETIC tachometer, figure 25.

The magnetic tachometer is driven by the synchronous motor. This synchronous motor rotates a permanent magnet. A metal drum surrounds the rotating magnet, and tries to rotate with it but is held back by a spring. When the airplane engine is

turning over slowly, the tachometer generator on the engine generates a low current, which causes the synchronous motor in the indicator to turn slowly. The rotating magnet rotates slowly. The drum TRIES to rotate slowly with the magnet, but is held back by the spring, and moves the indicator needle only a few points across the scale. When the engine turns over at high speed, the generator delivers a high current to the indicator synchronous motor. The magnet rotates at high speed, the drum TRIES to keep up, and the needle is pulled over to indicate high rpm.

A-c tachometers use no brushes, slip rings, or commutators. The entire system functions on low-frequency a. c. and causes no radio or compass interference.

Before starting the engine, check the wiring between the indicator and the instrument generator for a closed current. If the generator leads are shorted while the engine is running, a complete or partial loss of magnetic flux from the rotor may result. This loss of magnetic strength will change the operating characteristics of the generator, and make the tachometer read inaccurately.

The generator of the tachometer is designed for counterclockwise rotation. If the indicator on the instrument panel swings in the wrong direction, you must reverse two of the plug leads.

The generator is coupled to the engine by a special flexible rotor shaft which absorbs the sudden shocks of engine acceleration.

SYNCHRONIZER INDICATOR

In multi-engined aircraft, it is important to keep the engines running at the same speed. A SYNCHRONIZER INDICATOR will show any difference in engine speeds. In a twin-engined plane, the indicator contains a small electric motor connected by

leads to the tachometer generators on both engines. Any difference in speed between the two engines will cause a difference in the cycles generated by the two tachometer generators. This difference will make the synchronizer motor TEND to rotate its pointer to the right if the secondary engine is running faster than the master engine, or to the left if the master engine is running faster.

When the synchronizer indicator is installed, one engine is selected as the comparative master. The other engine is referred to as the secondary engine. The tachometer generator of the master engine is wired to the THREE-PHASE winding on the synchronizer, and the tachometer generator of the secondary engine is wired to the SINGLE-PHASE winding of the synchronizer. In operation, the synchronizer pointer will tend to rotate in a CLOCKWISE direction or to the right if the SECONDARY engine runs FASTER than the master. The synchronizer pointer will tend to rotate in a COUNTERCLOCKWISE direction or to the LEFT if the speed of the MASTER engine is GREATER than the secondary. However, the pointer will remain motionless in the center of the scale if the two engines are running at the same speed.

For aircraft with more than two engines, a selector switch is used to connect the single-phase winding of the indicator to the tachometer generator on the selected secondary engine. The extreme left engine is usually selected as the master engine.

TWO-WIRE SELSYN

You'll find Selsyn instruments used in several places on an airplane—to tell the pilot whether his landing wheels are up or down, to indicate the position of his wing flaps, and to tell him how much gasoline there is in each tank.

Here's the principle of the Selsyn instrument. Let's look at the operation of the 2-wire Selsyn as a

fuel gage, in figure 26. The principle is the same, no matter what you use the Selsyn to indicate.

In general, LIQUID LEVEL GAGES use a d-c Selsyn system. Two general types are used. The first type is designed to provide approximately 120° of

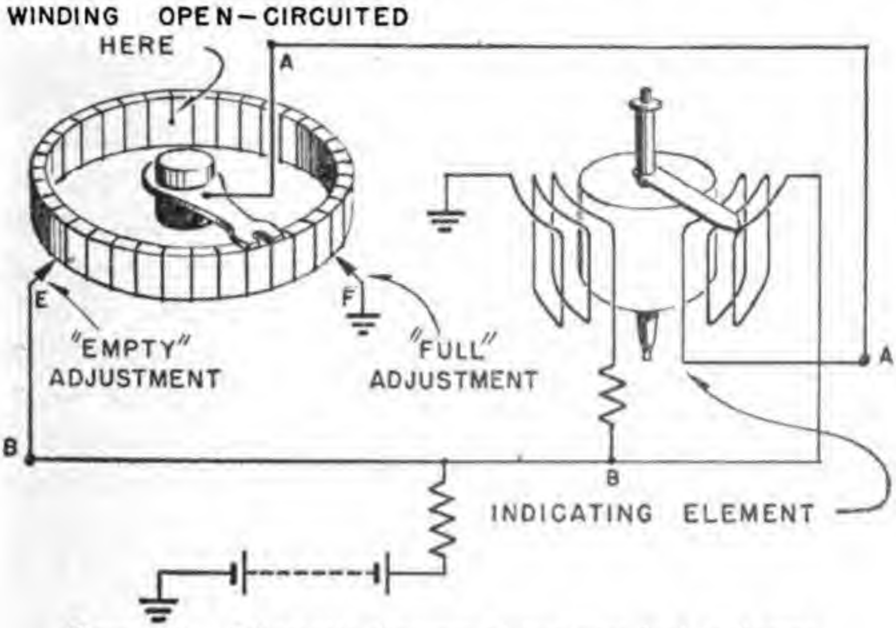


Figure 26.—Schematic diagram of two-wire fuel indicator.

indicator rotation, while the other allows 360° of rotation. The first type uses a TWO-WIRE system, and the second uses the THREE-WIRE system.

THE TRANSMITTER

The mechanical construction of the transmitters for both systems is practically identical. A float arm rises or falls as the level of the fuel in the tank changes. The motion of the float arm is transmitted through gears to a U-shaped magnet which surrounds a shell. This shell is spot-welded to the transmitter tube, and provides a liquid-tight seal between the tank and the electrical part of the fuel gage.

A diamond-shaped magnet inside the shell follows the motion of the U-shaped magnet outside the shell,

and causes rotation of the transmitter head shaft. This shaft is connected to the rotating arm or arms of the electrical transmitter.

TWO-WIRE GAGE SYSTEMS

The electrical transmitter consists of a resistance coil wound upon a circular form. Three contacts are made to the coil. Two of the contacts provide independent EMPTY and FULL adjustments. The third contact is made through a brush which moves around the wire-wound ring as the float arm moves.

The INDICATING DEVICE consists of a magnetized rotor surrounded by a damping cylinder. The two actuating coils are placed beyond the circumference of the damping cylinder and are mounted perpendicular to the cylinder, and at approximately 140° from each other. The principle of operation is based on creating a magnetic field around the coils. The field is created by flux in the actuating coils. The magnetized rotor is turned by this field, and

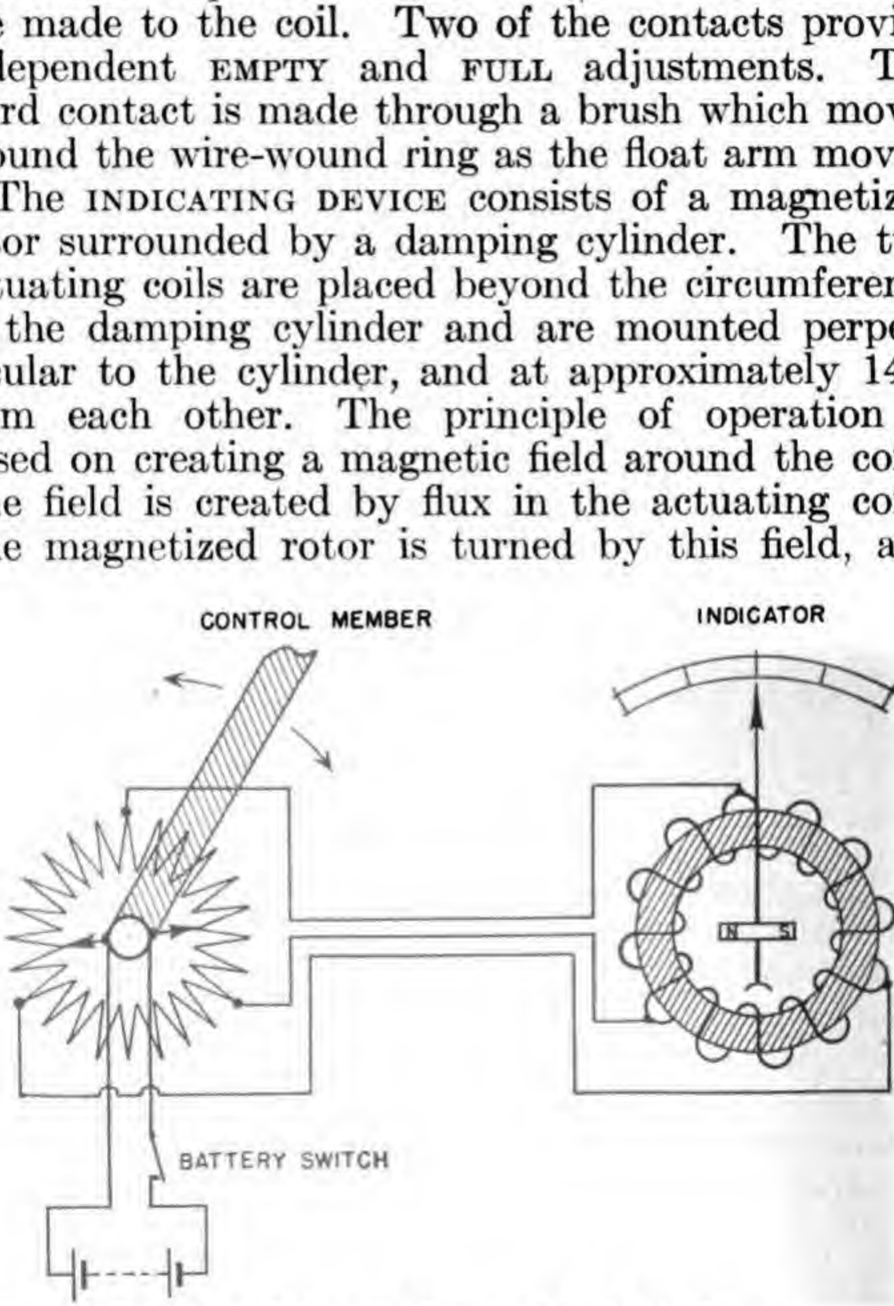


Figure 27.—Schematic diagram of 3-wire d-c Selsyn.

turns a pointer to indicate fuel level. Current and flux from one coil are fixed, but the current and flux in the other coil vary with the liquid level.

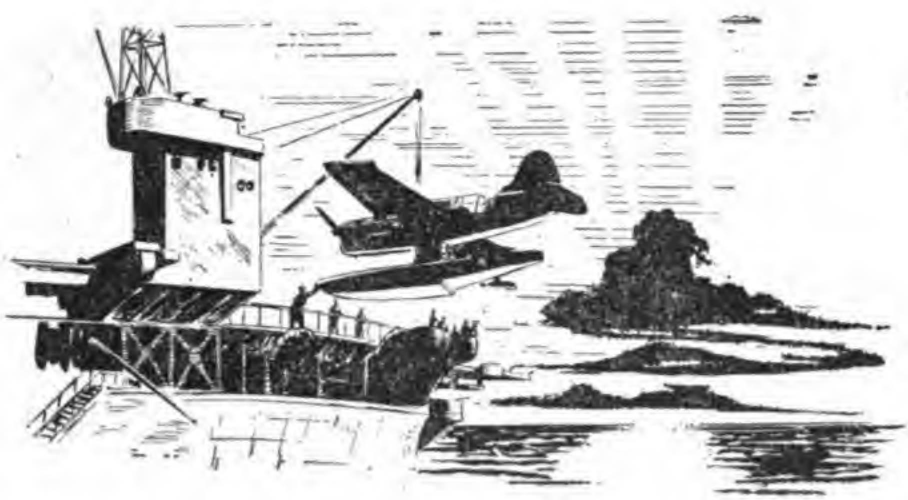
It is usually necessary to know the level in several tanks. Consequently, the indicator on the instrument panel often consists of several pointers—one pointer for each tank.

THREE-WIRE SYSTEM

The schematic diagram of the three-wire system is shown in figure 27. You can see that, electrically, this system is identical with the landing-gear indicator already described.

POSITION INDICATORS

There are various types of position indicators used in aircraft for indicating the position of the landing gear, flaps, etc. You will find that these indicators are usually identical electrically with one of the two fuel gage circuits you've already studied. The main differences are in the mechanical drives to the electrical transmitters, and the calibrations of the indicators.



CHAPTER 4

KIRCHOFF'S LAWS

AROUND THE CIRCUIT

In many electrical circuits, you'll find that the arrangement of the devices and applied voltages makes it almost impossible for you to solve such networks by simple applications of Ohm's Law. You can simplify these problems by the application of KIRCHOFF'S LAWS.

Here are the Laws:

IN ANY ELECTRICAL NETWORK, THE ALGEBRAIC SUM OF THE CURRENTS THAT MEET AT A POINT IS ZERO.

IN ANY COMPLETE ELECTRICAL CIRCUIT, THE SUM OF ALL THE EMF'S AND ALL THE VOLTAGE (IR) DROPS, TAKEN WITH THEIR PROPER SIGNS, IS ZERO.

FIRST LAW

Because the current in all parts of a SERIES circuit is the same, the current flowing AWAY from any given point in that circuit is equal to the current flowing INTO it. In other words, you get out just what you put in.

Look at figure 28. Use A as a focal point. You can see that the total current $(I_1+I_2+I_3)$ is the value of the current flowing TO that point. The current flowing away from A in the direction of point C is I_1 and that flowing in the direction of point B is I_2+I_3. Therefore, the current flowing AWAY from point A equals that flowing TO it. The current flowing TO a given point in a circuit is POSITIVE. Hence, current flowing AWAY from that point is NEGATIVE. In a

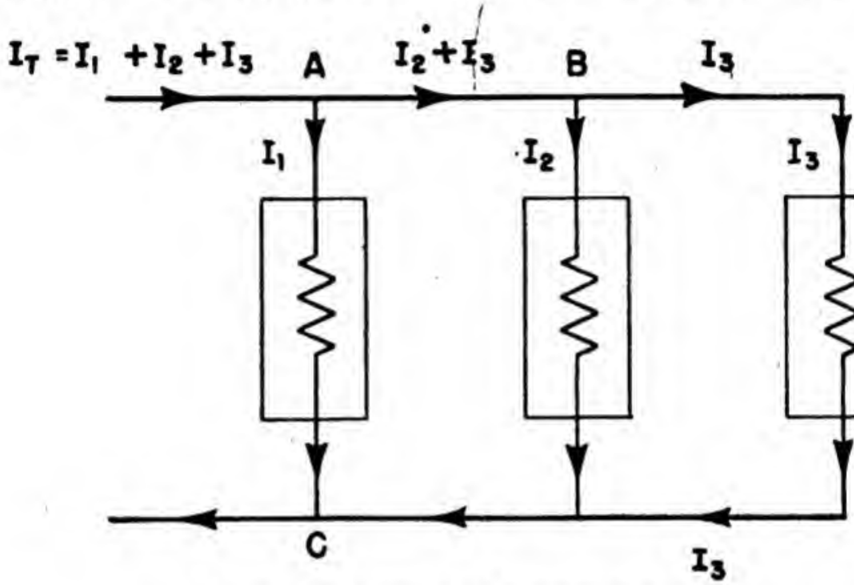


Figure 28.—Currents at a junction point.

practical application of the law as stated, $I_1+I_2+I_3-I_1-I_2-I_3=0$. This law is true for any point in the circuit.

SECOND LAW

Select some starting point in the circuit and follow a particular path around this circuit to the starting point. You will meet several voltage CHANGES. These changes are caused by voltage sources in the circuit and the IR voltage drop across any resistance in the circuit. In some cases, the change will be a voltage rise. In others, it will be a voltage drop.

The voltage across a battery and the IR drop across a resistor have polarities. Suppose you assign

a PLUS sign to each voltage RISE and a MINUS sign to each voltage DROP. According to KIRCHOFF'S SECOND LAW, the algebraic sum of these voltages, when added with proper polarity signs, is always zero. Be sure you understand the following problems—

SAMPLE PROBLEM NO. 1

You have a battery with an emf of 6 volts and an internal resistance of 0.10 ohm connected to a load circuit whose resistance is 9.9 ohms. Find the load current.

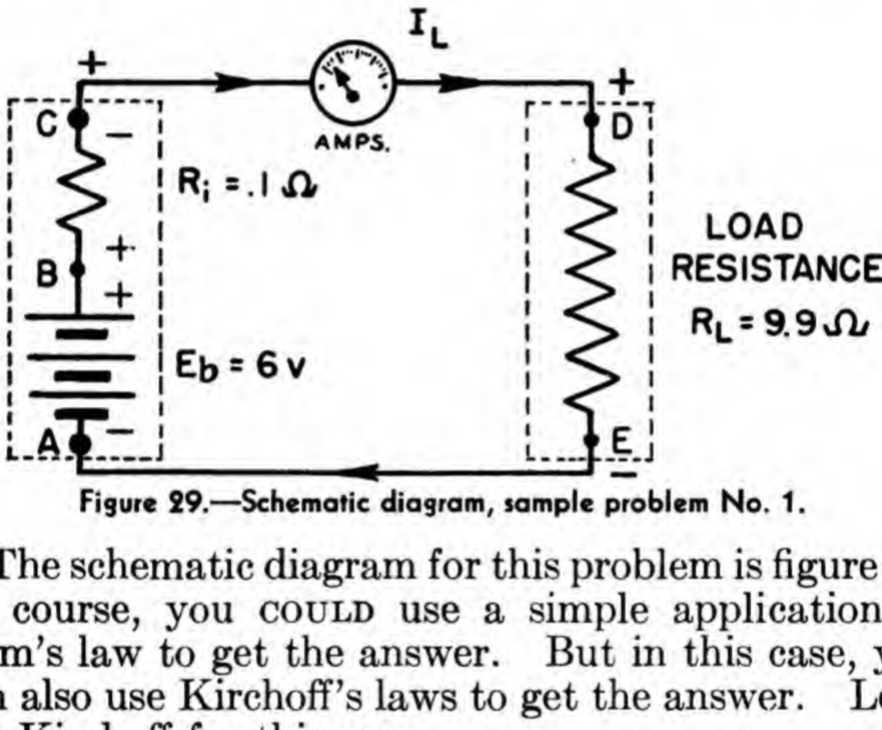


Figure 29.—Schematic diagram, sample problem No. 1.

The schematic diagram for this problem is figure 29. Of course, you COULD use a simple application of Ohm's law to get the answer. But in this case, you can also use Kirchoff's laws to get the answer. Let's use Kirchoff for this one.

Start at point A and pass around the circuit in a clockwise direction. A voltage increase occurs in passing across the battery. Because a voltage drop occurs across the internal resistance R_i of the battery whenever load current I_L flows, you must write down the battery emf E_b between points A and B and the I_LR_i drop between points B and C.

So that you can substitute these values in an equation, you must consider the polarity of each voltage

change. Point B is positive with respect to point A. Hence, the value of battery voltage substituted in the equation will be a positive number. In this particular circuit, the load current flows from B to C, and C is negative with respect to B. The voltage drop substituted in the equation will be a negative number.

If the wires have very little resistance, there will be no voltage drop from C to D and these points will have the same potential, or electrical pressure.

In passing across the load resistors R_L, the last drop in voltage occurs. You get this voltage drop by multiplying the load current by the load resistance, $E=IR$. You must also consider this drop a negative number since point E is negative with respect to point D.

Again if the wire leading back to A has very low resistance, you can neglect this voltage drop and consider point E to have the same potential as point A. And you are back at the starting point.

The algebraic addition of these voltage drops must always equal zero. Apply this law and you can solve for the load current, which in this case you do not know. Here's the general equation for the simple circuit of figure 29—

$$E_{(A\text{ to }B)}+E_{(B\text{ to }C)}+E_{(C\text{ to }D)}+E_{(D\text{ to }E)}+E_{(E\text{ to }A)}=0$$

or

$$+E_b-I_LR_i+0-(I_LR_L)+0=0$$

$$E_b-I_LR_i-I_LR_L=0$$

Substitute the known values in the equation, and you get a simple equation with one unknown, the LOAD CURRENT I_L.

$$6-0.1(I_L)-9.9(I_L)=0$$

$$6-10\ I_L=0$$

$$I_L=6/10=0.6\text{ ampere}$$

Here are THREE POINTERS to help you apply this law to other problems—

FIRST POINTER

In the more complicated problems, you can't always determine the direction of the current. So simply ASSUME A DIRECTION OF CURRENT FLOW. Just say to yourself, "It flows in THIS direction." If your assumption is backwards, your answer for current strength will be numerically correct, but will be a NEGATIVE number. Then you say to yourself, "The correct direction of current flow is in THAT direction. I guessed wrong."

NEXT POINTER

PLACE POLARITY MARKINGS ON ALL batteries and resistors in the circuit. The assumed current direction will not affect the battery polarities. But the voltage drop on resistors will be affected. And be sure you mark the voltage drops so that the resistor end at which current enters is positive. The other end, of course, will be negative.

LAST POINTER

By working your way around the circuit, SET UP EACH TERM OF THE EQUATION. Include all voltage sources and all voltage drops. In the equation, precede each term by the sign found on LEAVING each particular battery or resistor.

SAMPLE PROBLEM NO. 2

Figure 30 is like figure 29 EXCEPT that the current is assumed to flow in the OPPOSITE direction. Start at A. Pass around the circuit in a counterclockwise direction—the same direction as the ASSUMED current flows. Follow the rules and you obtain each term of the new equation.

In passing from point A to point E, you do not have to consider any voltage drop. In passing from

point E to point D, write the first term of the equation as I_LR_L and take the last sign on leaving this point. This makes the first term $(-I_LR_L)$. As you pass from point C to B, the second term becomes $-I_LR_i$. Again you take the sign at the end of the resistor as you leave. In going from B to A the last term becomes $-E_b$. Writing the terms in this

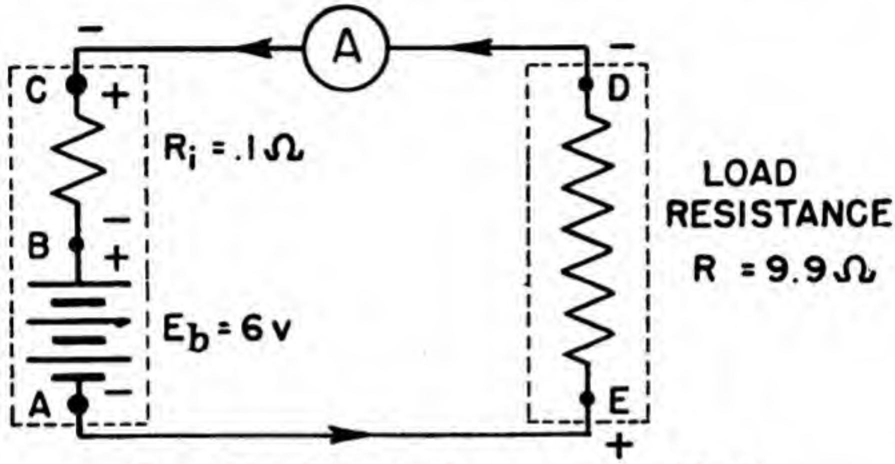


Figure 30.—Schematic diagram, problem No. 2.

same order and making them equal to zero, you get the following equation—

$$-R_LI_L-R_iI_L-E_b=0$$
$$-9.9(I_L)-0.1(I_L)-6=0$$
$$-10I_L=6$$
$$I_L=-6/10=-0.6 \text{ ampere}$$

The answer is NEGATIVE. So the ASSUMED direction of current flow was REVERSED.

SAMPLE PROBLEM NO. 3

A generator with an internal resistance of 0.01 ohm and an induced emf of 14 volts is connected through a series resistor to a battery having an emf of 12 volts and an internal resistance of 0.03 ohm. The series resistor has a value of 0.01 ohm. Determine the charging current.

The circuit diagram for this problem is in figure 31. The generator has a higher voltage, hence you can assume that the current will flow as shown by the arrows. After this assumption, you can insert the electrical polarity of voltage drops on all resistors. By starting at *A* and passing around the circuit in

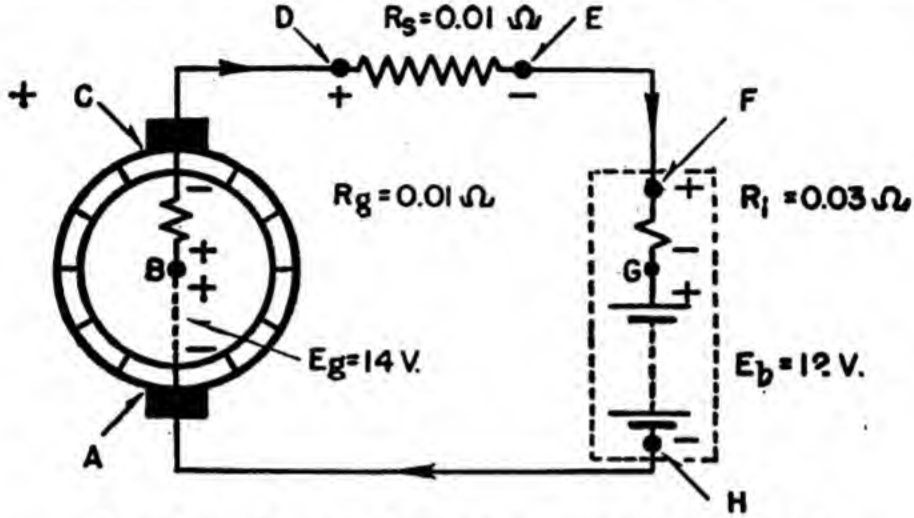


Figure 31.—Schematic diagram, sample problem No. 3.

the direction of the current, you can write the general equation—

$$\begin{array}{ccccc} (A \text{ to } B) & (B \text{ to } C) & (D \text{ to } E) & (F \text{ to } G) & (G \text{ to } H) \\ +E_g & -I_LR_g & -I_LR_s & -I_LR_l & -E_b=0 \end{array}$$

Substitute known values—

$$14-I_L(0.01)-I_L(0.01)-I_L(0.03)-12=0$$

$$14-0.05\ I_L-12=0$$

$$-0.05\ I_L+2=0$$

$$-0.05\ I_L=-2$$

$$I_L=\frac{2}{0.05}=40 \text{ amperes}$$

SAMPLE PROBLEM NO. 4

A load circuit with a resistance of 0.15 ohm is connected in parallel with a generator and battery. The induced emf of the generator is 28 volts and its

armature resistance is 0.2 ohm. The battery has an emf of 24 volts and an internal resistance of 0.1 ohm. Find (*a*) the terminal voltage of the battery, (*b*) the terminal voltage of the generator, (*c*) the current through the load circuit, (*d*) the current through the battery circuit, and (*e*) the current supplied by the generator.

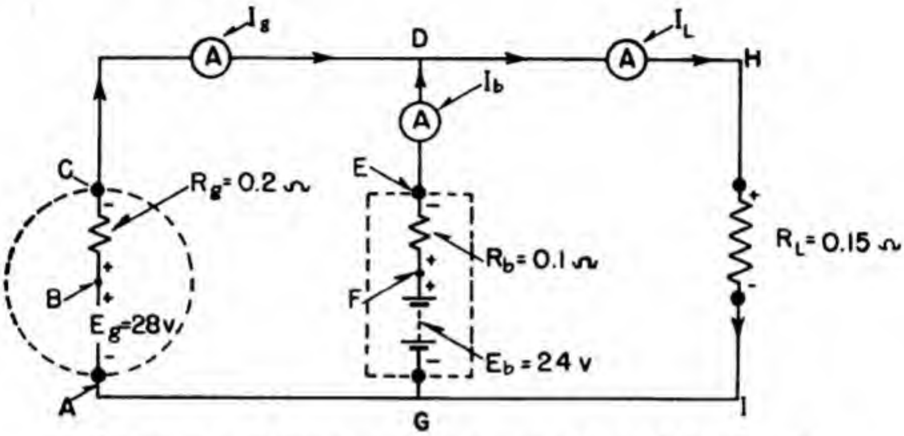


Figure 32.—Schematic diagram, sample problem No. 4.

You have the circuit diagram in figure 32. ASSUME the current direction shown by the arrows in the figure. Starting at *A* and going around the short path, *G*, *F*, *E*, *D*, *H*, *I*, and back to *G*, you can form the next equation—

1. $+E_g - I_g R_g + I_b R_b - E_b = 0$
2. $28 - I_g(0.2) + I_b(0.1) - 24 = 0$
3. $4 - I_g(0.2) + I_b(0.1) = 0$

By starting at *G* and passing around the other path, *G*, *F*, *E*, *D*, *H*, *I*, you can form the next equation—

4. $E_b - I_b R_b - I_L R_L = 0$
5. $24 - I_b(0.1) - I_L(0.15) = 0$

By considering the currents flowing TO and AWAY from the JUNCTION *D*, you can write—

6. $I_g + I_b = I_L$

By substituting the term (I_g+I_b) for I_L in Equation 5, you get—

7. $24-I_b(0.1)-(I_g+I_b)0.15=0$

or $24-0.1I_b-0.15I_g-0.15I_b=0$

8. $24-0.25I_b-0.15I_g=0$

Equations 3 and 8 both have I_g and I_b as the unknown quantities. By combining these equations, you can get an equation with only ONE UNKNOWN.

9. $24-0.25I_b-0.15I_g=0$

10. $4+0.1I_b-0.2I_g=0$

Now multiply equation 10 by 2.5 to make the I_b term in each equation have the same value. Then—

11. $24-0.25I_b-0.15I_g=0$

12. $10+0.25I_b-0.5I_g=0$

You can cancel the I_b term by ADDING the two equations (to answer Question *e*).

13. $34-0.65I_g=0$

$I_g=\frac{34}{0.65}=52.3$ amperes (Ans.)

You can obtain an equation with I_b (Question *d*) as the only unknown by substituting the known value of I_g in Equation 3—

14. $4-(52.3)(0.2)+0.1I_b=0$

$I_b=64.6$ amperes (Ans.)

The load current (Question *c*) is equal to the sum of the generator and battery currents—

$$I_L=I_b+I_g=64.6+52.3=116.9 \text{ amperes} \quad \text{(Ans.)}$$

The generator terminal voltage is the same as the battery terminal voltage (Questions *a* and *b*). The battery voltage will be equal to the battery emf minus the drop across the internal resistance—

$$E_t=24-0.1\ (64.6)=17.54 \text{ volts} \quad \text{(Ans.)}$$

SAMPLE PROBLEM NO. 5

A generator, battery, and load circuit are connected as shown in the preceding problem. The generator voltage, armature resistance, battery emf, and internal resistance have the same values as in the preceding problem. But, in this case the load current is to be 150 amperes. Find: (*a*) The current supplied by the generator, (*b*) the current supplied by the battery, (*c*) the generator terminal voltage, (*d*) the battery terminal voltage.

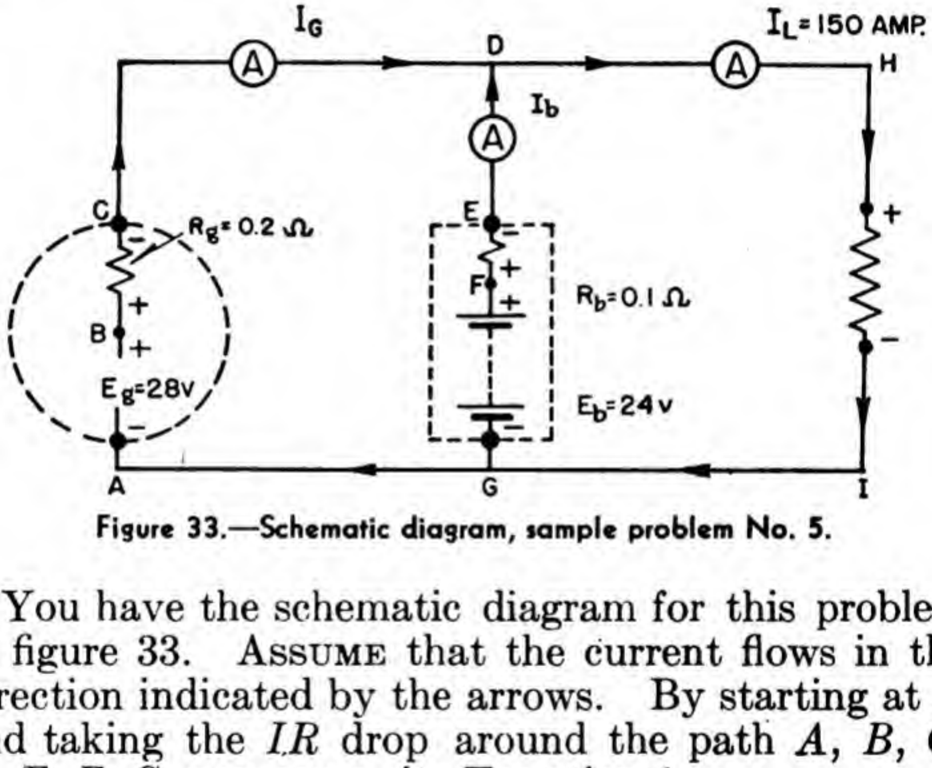


Figure 33.—Schematic diagram, sample problem No. 5.

You have the schematic diagram for this problem in figure 33. ASSUME that the current flows in the direction indicated by the arrows. By starting at *A* and taking the *IR* drop around the path *A*, *B*, *C*, *D*, *E*, *F*, *G*, you can write Equation 1—

1. $E_g - I_gR_g + I_bR_b - E_b = 0$

This equation contains two unknown quantities. You can reduce it to an equation with one unknown quantity by considering the relation between currents at junction *D*, using Kirchoff's First Law. Equations 2 and 3 express this relationship.

2. $I_b + I_g = I_L = 150$
3. $I_b = 150 - I_g$

By substituting this general value of I_b in Equation 1, you obtain Equation 4. Solve Equation 4 for its one unknown quantity—the generator current—(Question *a*).

$$4.\quad E_g - I_gR_g + I_bR_b - E_b = 0$$

$$28 - 0.2I_g + 0.1(150 - I_g) - 24 = 0$$

$$4 - 0.2I_g + 15 - 0.1I_g = 0$$

$$-0.3I_g = -19$$

$$I_g = 63.33 \text{ amperes} \quad \text{(Ans.)}$$

You can find the battery current (Question *b*) by substituting this value of generator current in Equation 3.

$$I_b = 150 - I_g \quad \text{(Eq. 3)}$$

$$I_b = 150 - 63.33$$

$$I_b = 86.67 \text{ amperes} \quad \text{(Ans.)}$$

Terminal voltage of generator (Question *c*)—

$$E_g - I_gR_g = 28 - (63.33(0.2))$$

$$= 28 - 12.67$$

$$= 15.33 \text{ volts} \quad \text{(Ans.)}$$

Terminal voltage of battery (Question *d*)—

$$E_b - I_bR_b = 24 - (86.67)(0.1)$$

$$= 24 - 8.67$$

$$= 15.33 \text{ volts} \quad \text{(Ans.)}$$

And there you have it!

SAMPLE PROBLEM NO. 6

A generator with an induced emf of 28 volts and an armature resistance of 0.2 ohm is connected in parallel with a battery and load circuit as in figure 34. The battery emf is 24 volts and its internal resistance is 0.1 ohm. Find (*a*) the value of the load current when the battery is FLOATING ON THE LINE, (*b*) the terminal voltage and current through the

generator, and (*c*) the terminal voltage and current through the generator when the load switch is open.

A BATTERY FLOATS ON A LINE when the CURRENT through it is ZERO. Under this condition, the generator terminal voltage must be exactly equal to the

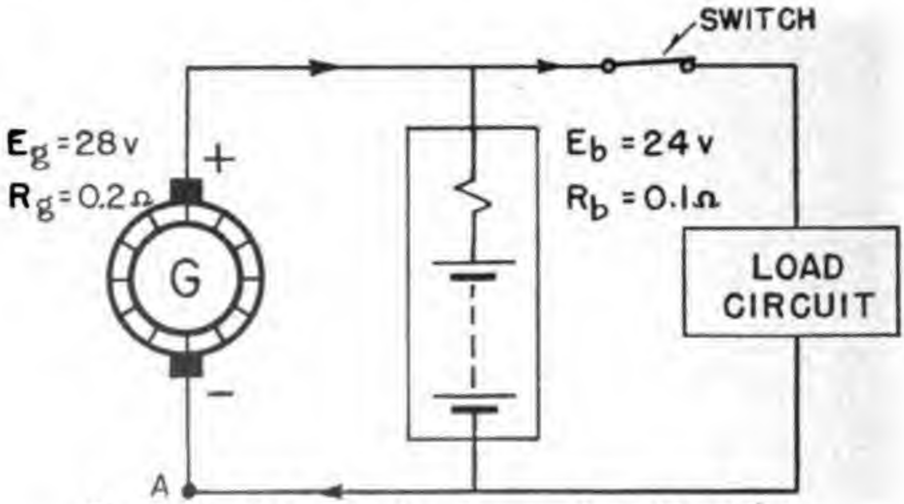


Figure 34.—Schematic diagram, sample problem No. 6.

battery emf. The following equation expresses this fact—

$$E_g - I_g R_g = E_b$$

Since $I_g = I_L$, substitute.

Then, $I_L R_g = E_g - E_b = 28 - 24 = 4$ volts

$$I_L R_g = 4$$

$$I_L = \frac{4}{R_g} \quad \frac{4}{0.2} = 20 \text{ amp.} \quad \text{(Ans.)}$$

Next, generator terminal voltage—

$$E_g - I_g R_g = 28 - 20(0.2)$$
$$= 28 - 4$$
$$= 24 \text{ volts} \quad \text{(Ans.)}$$

If the load switch is opened, there is only one path for current—through the battery. Start at *A*, and pass around the generator-battery circuit. You obtain—

$$E_g - I_g R_g - I_b R_b - E_b = 0$$

Since $I_b = I_g$

$$28 - 0.2I_g - 0.1I_g - 24 = 0$$
$$-0.3I_g = -4$$
$$I_g = 13.33 \text{ amperes}$$

Generator terminal voltage—

$$E_g - I_gR_g = 28 - 0.2(13.33)$$
$$= 28 - 2.67$$
$$= 25.33 \text{ volts} \quad \text{(Ans.)}$$

Battery terminal voltage—

$$E_b + I_bR_b = 24 + 0.1(13.33)$$
$$= 24 + 1.33$$
$$= 25.33 \text{ volts} \quad \text{(Ans.)}$$

Now work out these sample problems to test your ability to apply KIRCHOFF'S LAWS. The answers are given on page 71. But work 'em out before you look!

SAMPLE PROBLEM NO. 7

Two batteries, A and B, having emf's of 5 and 4 volts, and internal resistance of 1.2 and 1.0 ohms respectively, are connected in parallel as in figure 35. A resistor, R_L, of 2.5 ohms, is connected between their

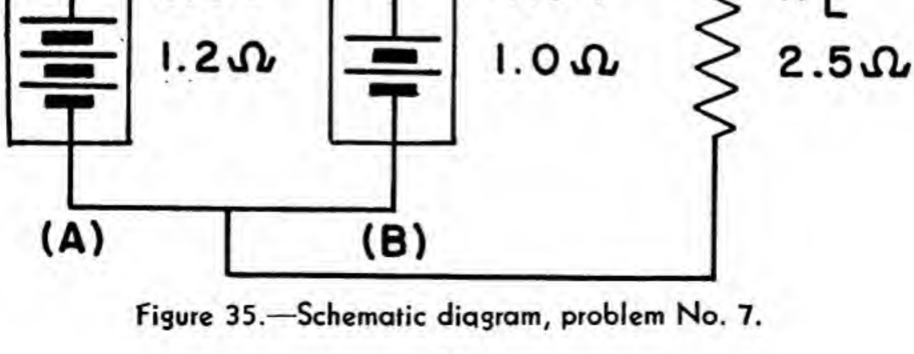


Figure 35.—Schematic diagram, problem No. 7.

common terminals. Find: (*a*) The current through the resistor, (*b*) the current through each battery, (*c*) the terminal voltage of the combination.

SAMPLE PROBLEM NO. 8

A storage battery having an emf of 8 volts and an internal resistance of 0.5 ohm is connected in opposition across a 20-volt source with an internal resistance of 0.1 ohm shown in figure 36. The resistance of all connecting wires is 1 ohm. Find: (*a*) The current through the battery, (*b*) the terminal voltage of the battery.

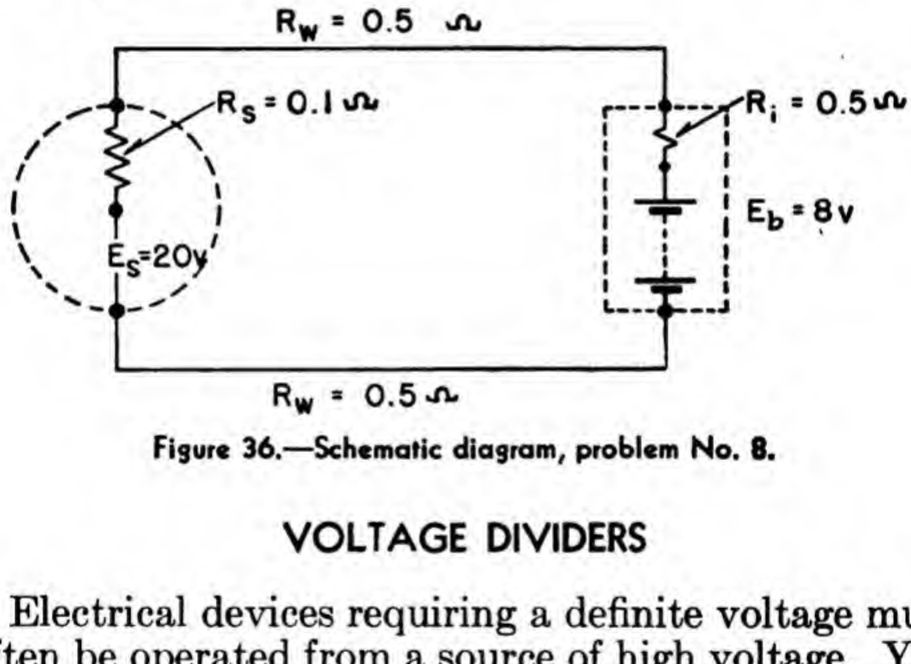


Figure 36.—Schematic diagram, problem No. 8.

VOLTAGE DIVIDERS

Electrical devices requiring a definite voltage must often be operated from a source of high voltage. You can then use a VOLTAGE-DROPPING RESISTOR or a VOLTAGE-DIVIDER.

You see the simplest form of voltage-drop circuit in figure 37. A device that requires 12 volts at 2 amperes is to be operated from a 48-volt source. The voltage-dropping resistor is placed in series with the electrical device. This is a series circuit. And the voltage across each unit will be in proportion to its resistance. If resistor R_1 has the proper value,

the voltage across it can be made the difference between 48 volts and 12 volts (or 36 volts). The current through each device in a series circuit is always the same. Hence, the current through R_1 must also be 2 amperes. By a simple application of Ohm's law, you find the resistance of R_1.

$$R_1=\frac{E_1}{I_1}=\frac{36}{2}=18 \text{ ohms}$$

Occasionally you must operate several low-voltage devices from a single high-voltage source. In this

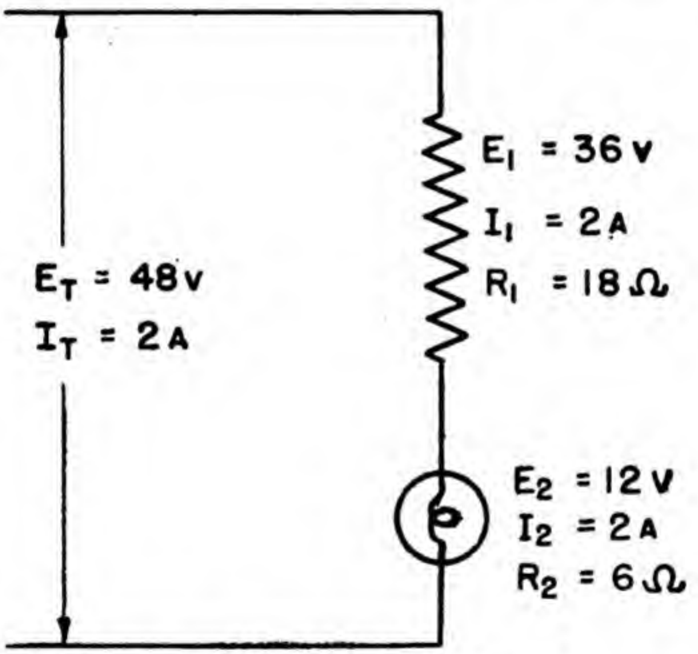


Figure 37.—Voltage-drop circuit.

case, you can insert a SERIES RESISTOR for each separate device. But when the number of devices is large and more than one device operates at the same voltage value, you may advantageously use a VOLTAGE-DIVIDER CIRCUIT.

In figure 38, you have the voltage-divider circuit that provides a series of lower voltages from a high voltage source. Here the devices of the circuit are to be operated at two different voltage levels. The

three resistance units connected to the source make up the voltage-divider circuit.

You can find the resistance elements that comprise this voltage-divider circuit only if you know the number of devices, the voltage of each device, and the current for each device, and you must know the voltage-current characteristic of the power supply.

Most power supplies, particularly auxiliary power devices, such as "B" supplies for radio receivers,

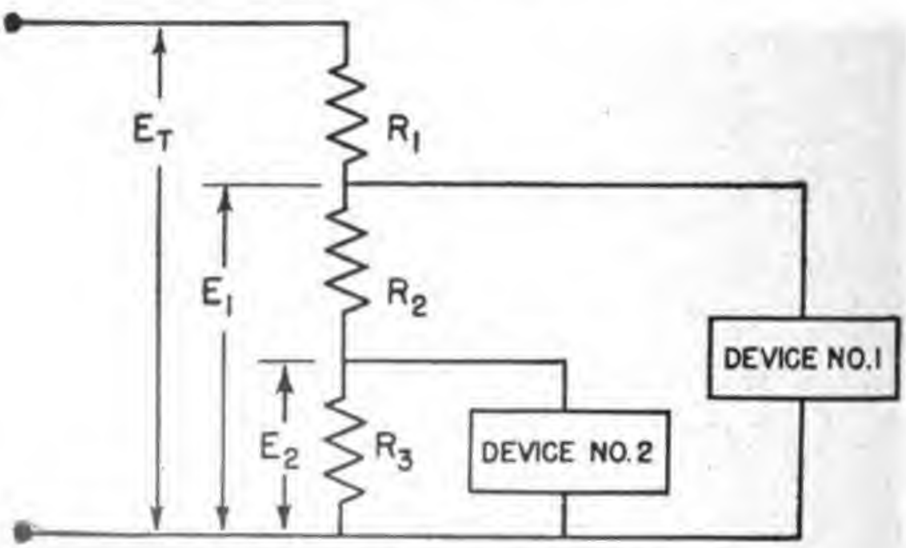


Figure 38.—Voltage divider circuit.

have a certain amount of internal resistance. So the voltage obtained at the power supply terminals varies with the current output. When the terminal voltage of the power supply remains CONSTANT over a wide range of current output, the power supply is said to have GOOD regulation. If the voltage drops off rapidly as the current drain is increased, the unit is said to have POOR regulation.

If you are to design a voltage-divider for use with a power supply that has poor regulation, you must know the terminal voltage of the power supply at the maximum total value of current required by the load circuits and the voltage-divider. If you do not have this information, you can easily get it by

determining the regulating characteristic of the supply.

You have in figure 39 a simple circuit that helps you obtain these data. Connect a variable resistance across the terminals of the power supply. By varying this resistance, you determine the terminal voltage over a wide range of load-current values. If you plot these values in a graph, you obtain a characteristic curve similar to that of figure 39 (*B*). With the information contained in this graph, you can design a voltage-divider or alter any existing

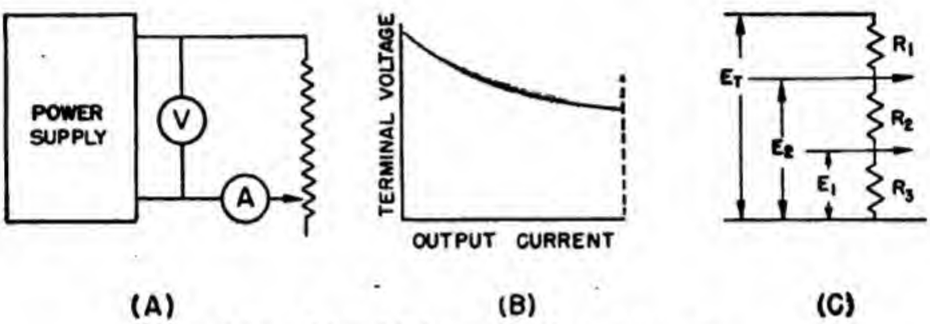


Figure 39.—Voltage regulation circuit.

voltage-divider as changes in the load circuit occur. But—

Before proceeding with the actual design of a voltage-divider, you must get one more value. Look at figure 39 (*C*). When TWO voltage levels are required, you use THREE resistors. Resistor R_3, referred to as the BLEEDER RESISTOR, stabilizes the voltage at the other taps. When the power supply has excellent regulation and the current drawn from the taps is fairly constant, you may eliminate this resistor. Because power supplies rarely have excellent regulation, this third resistor is usually included.

The current through the bleeder resistance is known as the BLEEDER CURRENT. Any current through this resistor is wasted in heat. The value of current chosen is a compromise between voltage-stability and

power loss. The choice will also depend on the characteristics of the individual power supply, and the type of electrical devices operated from the various taps. A representative value for bleeder current would be between 5 percent and 10 percent of the full-load current.

SAMPLE PROBLEM

The power supply is to be used to operate four different circuits, figure 40, each of which requires separate voltage. The devices in circuit 1 require 6 amperes at 48 volts. Circuit 2 contains devices that

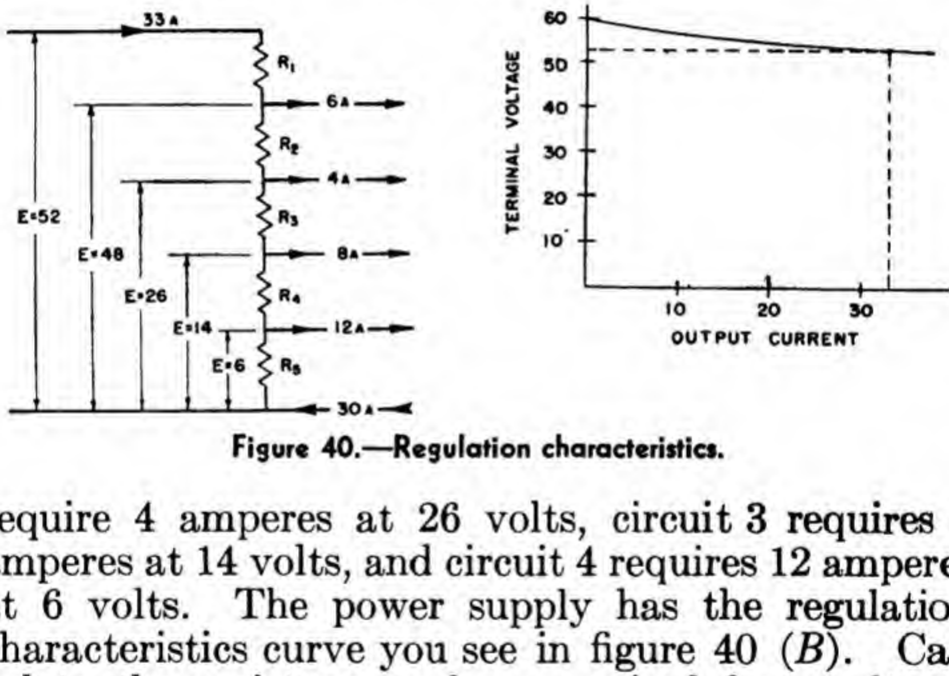


Figure 40.—Regulation characteristics.

require 4 amperes at 26 volts, circuit 3 requires 8 amperes at 14 volts, and circuit 4 requires 12 amperes at 6 volts. The power supply has the regulation characteristics curve you see in figure 40 (*B*). Calculate the resistance values required for a voltage-divider circuit.

In the figure, you have the general set-up of the divider circuit. There are five separate resistors connected in series across the power supply. The connections between resistors serve as taps for leading off the current to the different circuits. The voltage between each tap and the negative terminal of the supply must correspond to the voltage requirements of the circuit bridged across these points.

SOLUTION—

Load current $=6+4+8+12=30$ amperes

Bleeder current $=10$ percent of 30 amperes $=3$ amperes

Total current $=30+3=33$ amperes

The graph shows that the power supply has a terminal voltage of 52 volts at 33 amperes.

THEN—

R_1 must drop the voltage from 52 volts to 48 volts

Voltage drop across $R_1=52-48=4$ volts

Current in $R_1=33$ amperes

$$R_1=\frac{E}{I}=\frac{4}{33}=0.12 \text{ ohm.}$$

R_2 must drop the voltage from 48 to 26 volts

Voltage drop across $R_2=48-26=22$ volts

Current through $R_2=33-6=27$ amperes

$$R_2=\frac{E}{I}=\frac{22}{27}=0.81 \text{ ohm}$$

R_3 must drop the voltage from 26 to 14 volts

Voltage drop across $R_3=26-14=12$ volts

Current through $R_3=27-4=23$ amperes

$$R_3=\frac{E}{I}=\frac{12}{23}-0.52 \text{ ohm}$$

R_4 must drop the voltage from 14 to 6 volts

Voltage drop across $R_4=14-6=8$ volts

Current through $R_4=23-8=15$ amperes

$$R_4=\frac{E}{I}=\frac{8}{15}=0.53 \text{ ohm}$$

R_5, the bleeder resistor, must drop the voltage from 6 to 0 volts

Voltage drop across $R_5=6-0=6$ volts

Current through $R_5=15-12=3$ amperes (bleeder current)

$$R_5=\frac{E}{I}=\frac{6}{3}=2 \text{ ohms.}$$

ANOTHER SAMPLE PROBLEM

Four lamps are to be operated from a 100-volt source which has excellent regulation. The voltage and current requirements for each lamp are—

Lamp #1—100 volts; 3 amperes
Lamp #2—80 volts; 4 amperes
Lamp #3—48 volts; 3 amperes
Lamp #4—12 volts; 2 amperes

Design a voltage-divider for this circuit. See figure 41. Assume that the source has a terminal voltage of 100 volts at the required current drain.

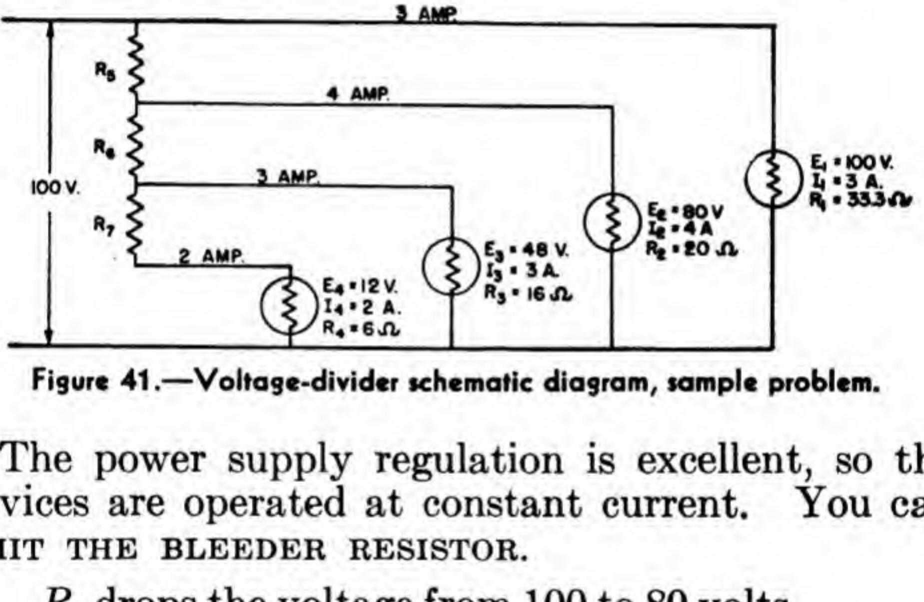


Figure 41.—Voltage-divider schematic diagram, sample problem.

The power supply regulation is excellent, so the devices are operated at constant current. You can OMIT THE BLEEDER RESISTOR.

R_5 drops the voltage from 100 to 80 volts
Voltage-drop across $R_5 = 100 - 80 = 20$ volts
Current through $R_5 = I_2 + I_3 + I_4 = 9$ amperes

$$R_5 = \frac{E}{I} = \frac{20}{9} = 2.22 \text{ ohms}$$

R_6 drops the voltage from 80 to 48 volts
Voltage drop across $R_6 = 80 - 48 = 32$ volts
Current through $R_6 = I_3 + I_4 = 5$ amperes

$$R_6 = \frac{E}{I} = \frac{32}{5} = 6.4 \text{ ohms.}$$

R_7 drops the voltage from 48 to 12 volts
Voltage drop across $R_7 = 48 - 12 = 36$ volts
Current through $R_7 = 2$ amperes

$$R_7 = \frac{E}{I} = \frac{36}{2} = 18 \text{ ohms}$$

ANSWERS TO PROBLEMS ON PAGES 63–64

Problem No. 7

(*a*) 1.463 amps.
(*b*) 1.119 amps.; 0.344 amp.
(*c*) 3.657 volts

Problem No. 8

(*a*) 7.5 amps
(*b*) 11.75 volts

CHAPTER 5

THEORY OF A-C CIRCUITS

WHICH TO USE—A. C. or D. C.?

You will run into very little a. c. on Navy aircraft. But because of that little, you should know what a. c. is, how it's generated and some of its characteristics. After all, 90 percent of the electricity ashore is a. c.

Now you're probably wondering why we have TWO kinds of current—a. c. and d. c. Why not pick out the best one and toss away the other one? Well, they're BOTH good. For certain jobs, one has advantage over the other.

FOR INSTANCE—

You can generate a. c. at higher voltages than d. c.

You can step-up or step-down a. c. with simple stationary transformers, while you have to use complicated rotary motor-generator sets with many moving parts to change the voltage of d. c.

You can transmit a. c. at high voltage over long distances without any great loss of power.

You can build large, high-speed a-c generators that will produce a. c. cheaply and efficiently.

You can use a. c. to run induction motors, which are highly efficient, run at constant speed, and have no complicated commutator. This is a real advantage to the use of a. c. in shops and plants.

BUT—

You still need d. c. for use with electric welding equipment, arc lights, and electro-chemical processes. And you'll need d. c. where you have to use variable-speed motors, such as streetcar and electric locomotive motors, elevator and printing-press motors, and other uses. It's much easier to vary the speed of a d-c motor than of an a-c motor.

INDUCED VOLTAGES

You know that a current is induced in a wire when you move the wire through a magnetic field, as in figure 42.

If you move the wire DOWN through the magnetic field, the current induced in the wire will flow in one direction. If you move the wire back UP, the in-

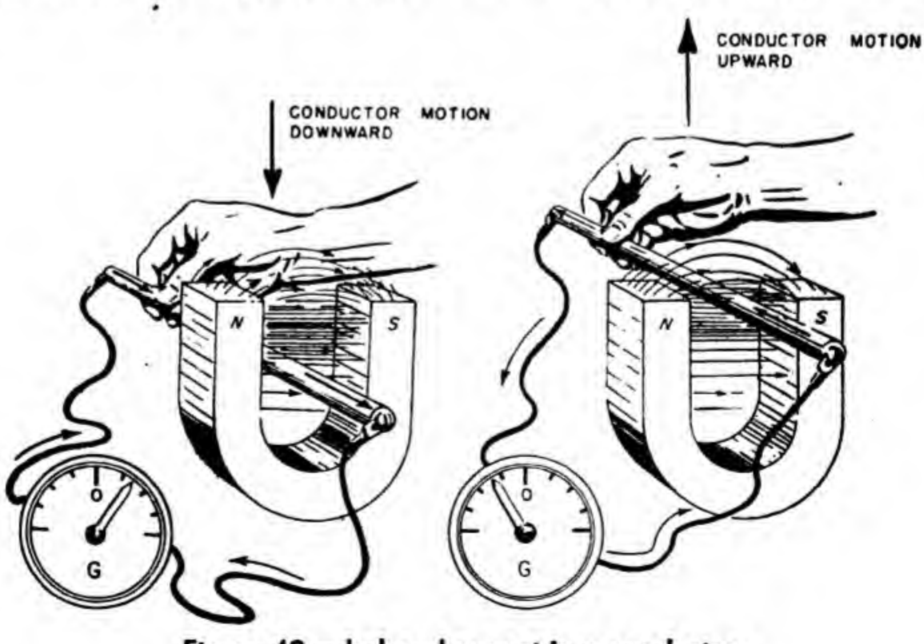


Figure 42.—Induced current in a conductor.

duced current will flow in the opposite direction.

And that's the foundation for the generation of a. c.! It's as simple as that, in theory.

Now look at the stop-motion pictures of a wire loop turning in a magnetic field. They're in figure 43, and you'll quickly recognize them as old friends.

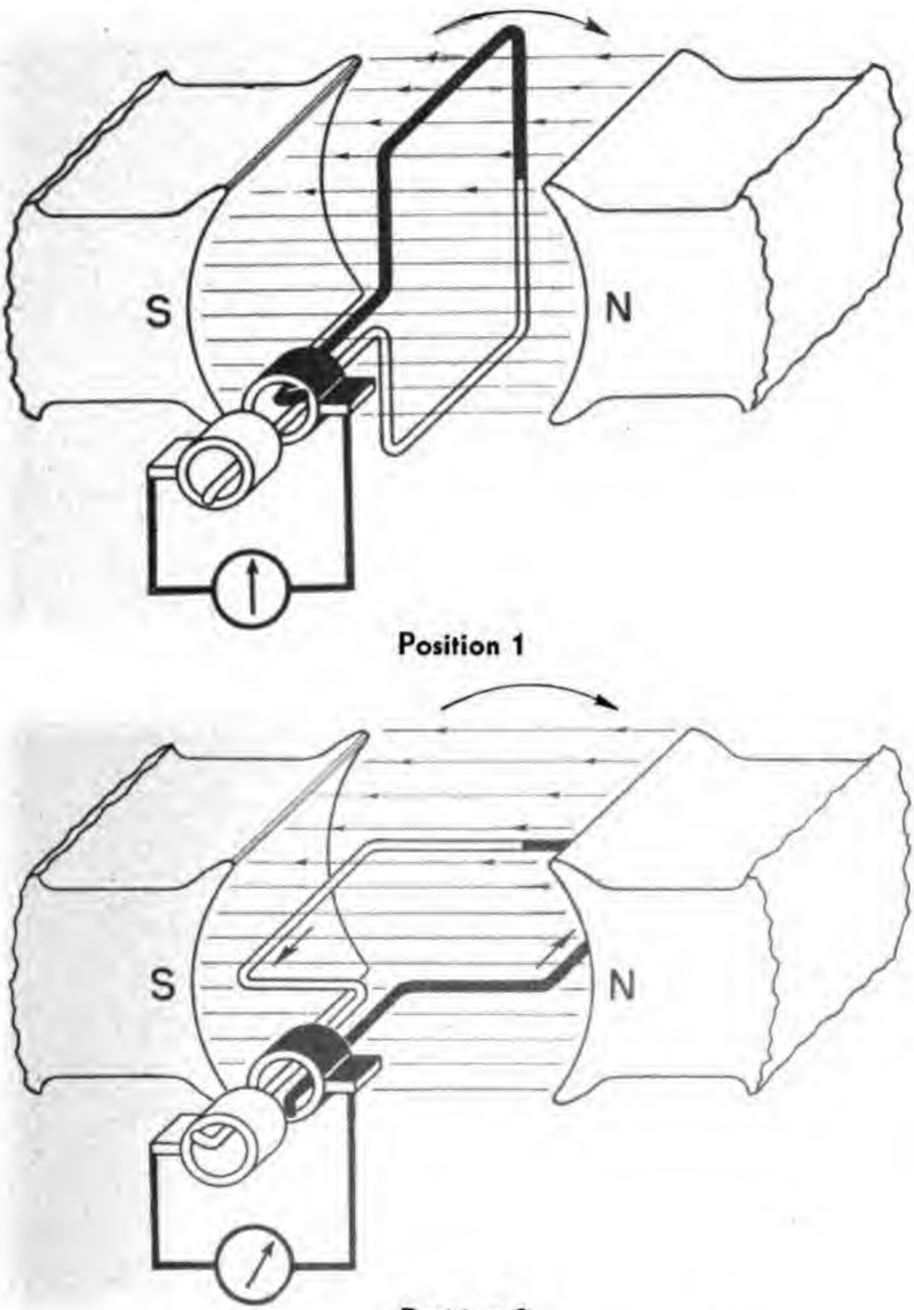
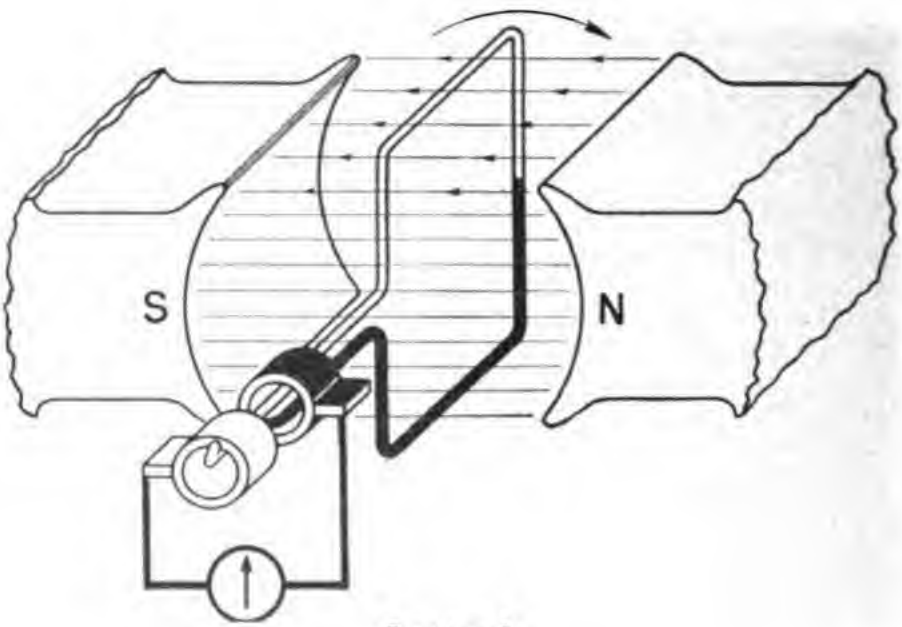
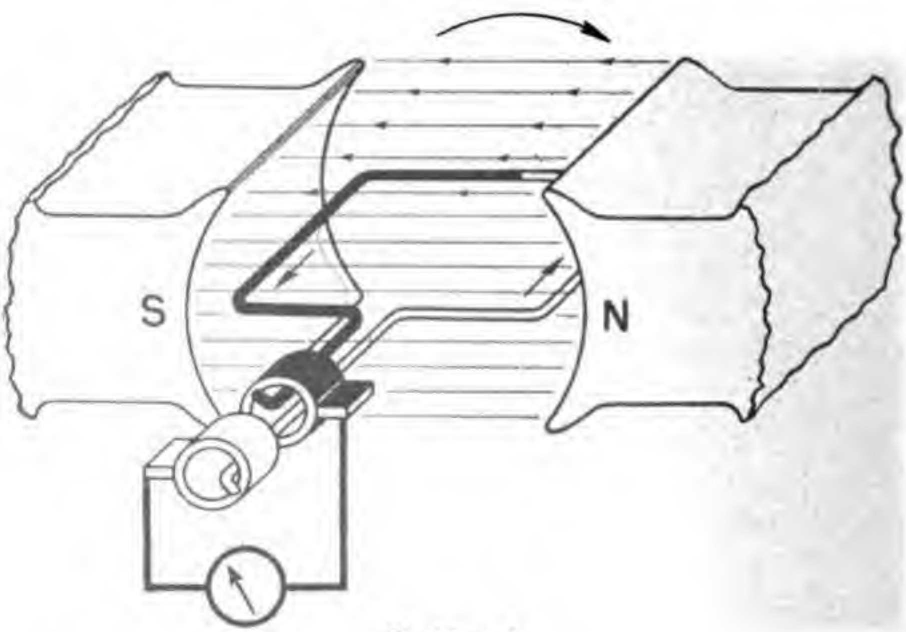


Figure 43.—Rotating loop in magnetic field.



Position 3



Position 4

Figure 43—Continued

When the loop is in position *1*, the conductors are cutting NO lines of flux, so the induced voltage through the loop is ZERO. When the loop moves to position *2*, the conductors cut a maximum number of lines of flux, and voltage through the loop is a maxi-

mum positive. Next the loop moves on to position *3*, and cuts NO lines of flux, so voltage sinks back to zero. With the loop in position *4*, a maximum negative voltage flows through the loop. Then the loop moves on to position *1* again.

Now, if you chart the amount of voltage that flows as the loop turns a full revolution, through 360°, you get a curve that looks like figure 44. This is a SINE CURVE. You can see that it indicates the induced voltage at any given point in the rotation of the loop.

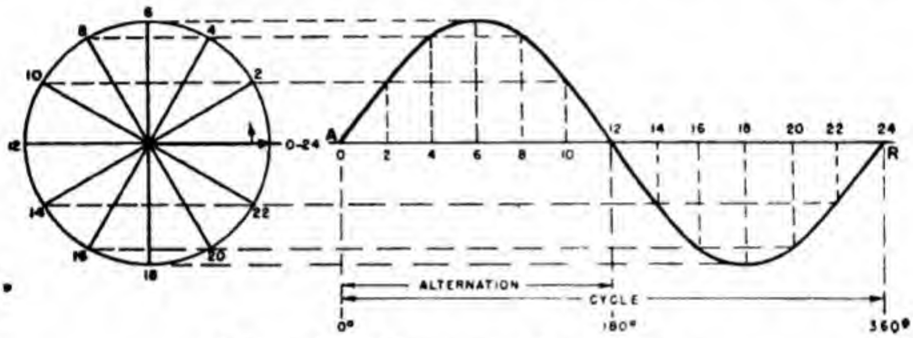


Figure 44.—Sine curve of a-c voltage.

CYCLES AND FREQUENCIES

You may remember that the electricity at home is 110 volts, 60-CYCLE, a. c. The "60-cycle" means that it has a FREQUENCY of 60 cycles per second. Or the current and voltage change their direction twice per cycle, or 120 times a second. You see, the current in the single-loop conductor of figure 43 goes from zero to maximum positive to zero in 180° or a half rotation of the loop. Then current goes from zero to maximum negative and back to zero in the second half of the rotation. The loop has completed a cycle, and the induced current has made TWO alternations.

The current or voltage makes a complete cycle every time it passes a pair of poles (a north and a south pole). In the simple one-loop machine you have only one pair of poles, so one revolution of the loop makes one cycle of current induced. TWO pairs

of poles would let you generate TWO cycles of induced current per revolution of the loop.

To generate 60-cycle current, a machine having a single pair of poles would have to rotate at—

60	$\times$	60	=	3,600
(cycles per second)		*(seconds per minute)*		*(revolutions per minute)*

A machine with TWO pairs of poles (called a 4-pole machine) would have to turn only half as fast to generate the same 60-cycle frequency, since ONE revolution of this machine generates TWO cycles.

And so you get a formula for FREQUENCY. If you know the speed, V, of the machine in rpm and the number of PAIRS of poles, P, in the machine, the generated frequency, F, will be equal to—

$$F=\frac{PV}{60}$$

For example, a 2-pole machine has ONE PAIR of poles, and rotates at 3,600 rpm. What's its frequency?

$$F=\frac{1\times 3{,}600}{60}=60 \text{ cycles (per second)}$$

If you know how many cycles you want to get out of a certain machine, but need to find out HOW FAST the machine must turn to generate 60-cycle voltage, turn the formula round so that—

$$V=\frac{60F}{P}$$

For example, in a 4-pole machine (2 pairs)—

$$V=\frac{60F}{P}=\frac{60\times 60}{2}=1{,}800 \text{ rpm.}$$

EFFECTIVE VALUE OF A. C.

If you want to find the EFFECTIVE or usable value of a. c. from your sine curve, you can't just glance at the highest peak of one loop of the sine curve. The

voltage or current charted by the sine curve is changing throughout the alteration from a value of zero to maximum and back to zero. Result—you have to determine the EFFECTIVE value of the a. c. If you take the PEAK value of current or voltage—that highest point to which your sine curve climbs or drops before it turns back down or up—and multiply that value by $\frac{1}{\sqrt{2}}$ or roughly 0.7, you'll come out with the EFFECTIVE value of the a. c. Or perhaps you know the effective voltage of the machine, and need to get the peak or maximum voltage. Multiply the effective voltage by 1.414, and you'll get the peak voltage.

For example, the sine curve for a certain a-c generator reaches a peak voltage of 110 volts. Then the effective voltage will be $0.7 \times 110 = 77$ volts. In other words, your 110-volt, a-c generator will generate an effective voltage capable of producing the same amount of POWER as would be produced by a 77-volt d-c generator.

You likewise use 0.7 as the multiplier for obtaining EFFECTIVE CURRENT when you know PEAK CURRENT.

CURVES IN PHASE

When you are walking in step with your girl, the two of you are in PHASE; but if she's taking one and one-half steps to your one, you're OUT OF PHASE. Since the voltage of an a-c generator causes the current to flow, the sine waves of current and voltage drawn or plotted on the same sheet will be a pair of curves that are IN PHASE, as in figure 45. That is, the curves cross the zero line together, and then reach their peaks at the same point of conductor rotation.

Actually, engineers usually design a-c generators and motors to operate so that the voltage reaches its peaks and zeros BEFORE or AFTER the current does. Then you say that the voltage is OUT OF

PHASE with the current. If the current curve reaches its peaks and zeros BEFORE the voltage curve, then the current is LEADING the voltage, and the voltage is LAGGING the current. By measuring the number of degrees of rotation that has taken

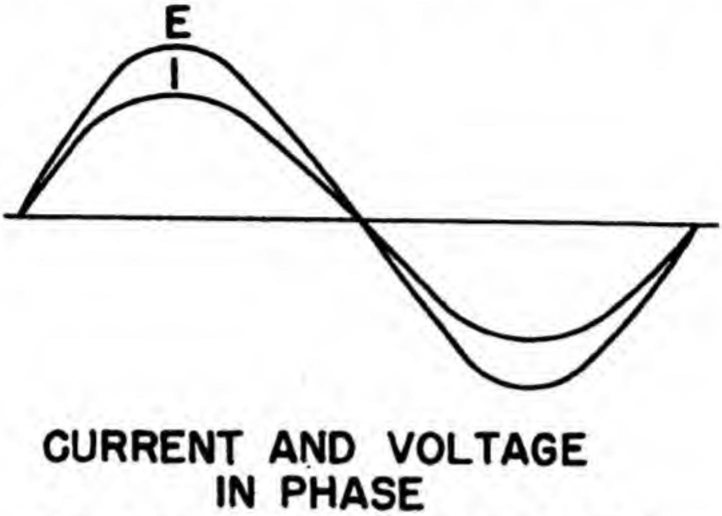


Figure 45.—Voltage and current curves in phase.

place between the time the leading curve crosses zero and the lagging curve crosses zero, you can find out how many DEGREES OUT OF PHASE the two curves are. For example, in figure 46, the current and voltage are out of phase, and the voltage LAGS the current by 30°, or the current LEADS the voltage by 30°. You can also describe this condition by saying that

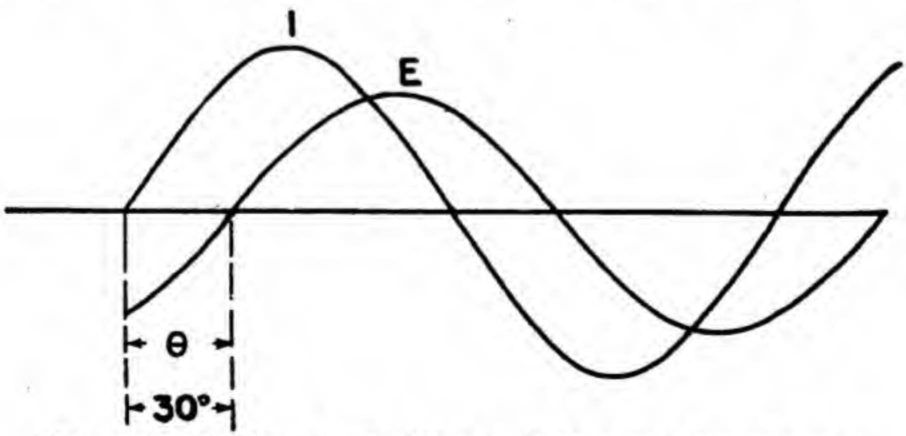


Figure 46.—Voltage curve 30° out of phase with current curve.

the PHASE ANGLE is 30°. And the symbol for phase angle is θ (Greek letter THETA).

VECTORS, AND WHAT THEY DO

Mathematicians have developed a mighty handy means to enable you to add FORCES together easily and quickly. The name for this method is VECTOR ADDITION. VECTORS are simply lines drawn to scale and in the proper direction to indicate the intensity and direction of the forces you want to add or subtract. For example, suppose a vector 1 inch long represents a force of 10 pounds, or perhaps 10 volts. Then a 2-inch vector would represent a force of 20 pounds, or 20 volts. You will use vectors and vector diagrams to analyze alternating currents and their emf's.

Suppose you have a small wagon loaded with batteries and tools that you want pulled across the hanger apron to a plane, and you find two men who want to help. The bigger fellow can pull 80 pounds and the little guy can pull 50 pounds. The little guy thinks you want the tools at a plane that's parked NNE of the tool room, while the big boy heads for a plane straight *E* of the tool room. What to do? Either let them pull and tug together in different directions, or throw them off the job and get one great big guy who can go in the right direction. Let's figure out by vectors what size man you'll need, and what his compass course will be. Look at figure 47.

Here's what you do. Lay out a scale diagram of the situation, with line *OA* representing the compass course and amount of pull of the little fellow. *OA* will be 5 units long, each unit representing 10 pounds of pull. Line *OC* represents the pull of the big guy and his path to the east, and is 8 units long, for 80 pounds total pull. Now you have two vectors—the one for the little man and the one for the big guy.

To get rid of the two men and replace them with one great big guy pulling in the right direction, you now lay off AB parallel to OC and of the same length as OC. Then lay off CB parallel to OA and of the same length as OA. Draw the diagonal line OB. That gives you the direction and the amount of pull your new man will have to exert. If you measure the length of OB you'll find that it is 10½

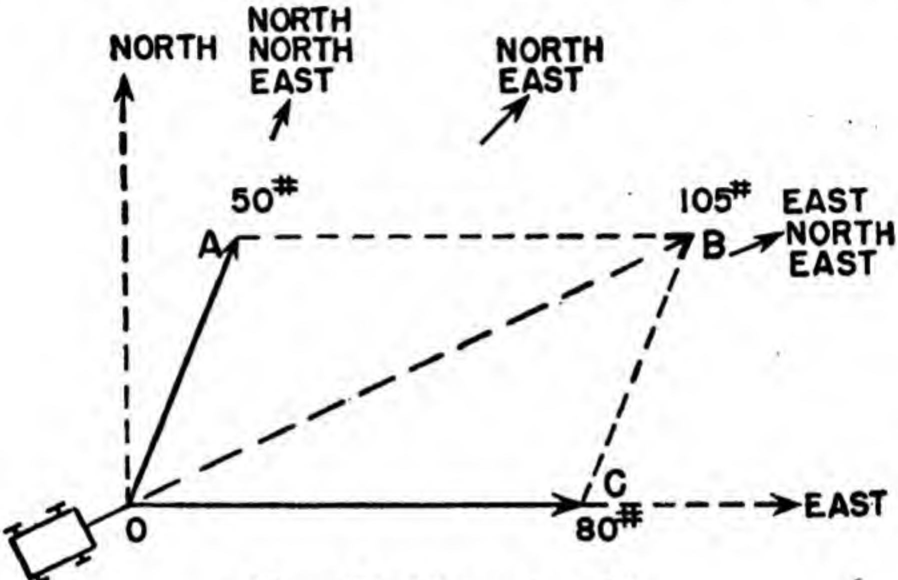


Figure 47.—How vectors add.

units, meaning that your new boy will have to be able to pull 105 pounds on a course a little north of ENE.

You see that you've solved a pretty complex problem without using a bit of math.

VECTORS AND SINE WAVES

And here's how vectors work in dealing with a. c. Look at figure 48, which is a combination of a SINE CURVE and a VECTOR DIAGRAM for a single loop armature rotating in a magnetic field and generating a peak voltage of 10 volts.

When the conductor is at 0°, or 3 o'clock position, it is cutting no lines of flux in the magnetic, field and

is generating no induced voltage. When the conductor moves up to 30°, or the 2 o'clock position, an induced voltage of 5 volts is generated and finally when the conductor reaches 90°, or 12 o'clock position, the peak voltage of 10 volts is induced.

You can see that if you allow your vector arrow to rotate along with the inductor, and then run a horizontal line from the arrowhead over to the line of peak voltage, such as line AX from the 2 o'clock position. you will be able to find the voltage at the 2 o'clock position. Just measure the length of line MX. It's half the length of OP, and OP represents the peak voltage of 10 volts, so MX must be 5 volts.

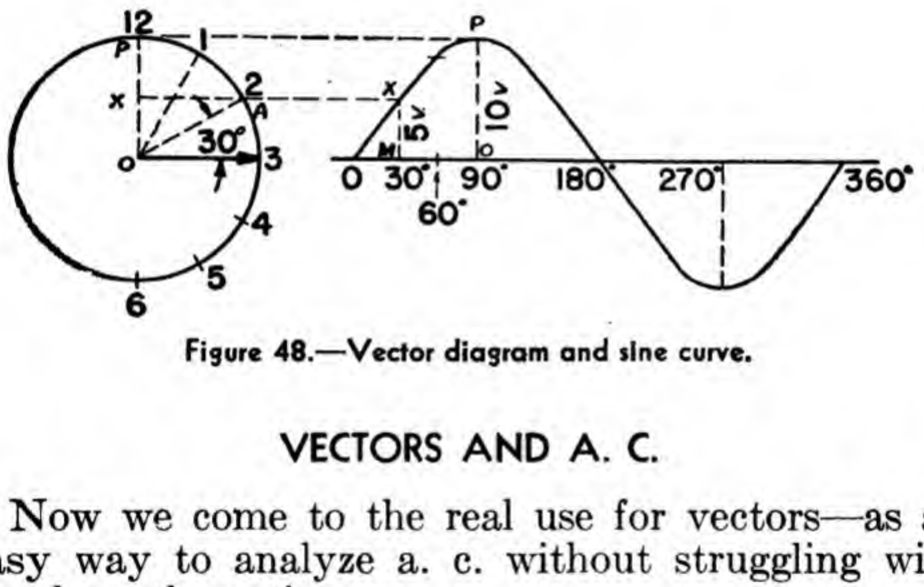


Figure 48.—Vector diagram and sine curve.

VECTORS AND A. C.

Now we come to the real use for vectors—as an easy way to analyze a. c. without struggling with tough mathematics.

Suppose you have an armature with TWO conductor loops on it—loop B being 30° behind loop A. When you rotate this two-loop armature in the magnetic field, loop A will be cutting a maximum number of lines of flux when loop B is only cutting about ¾ of the maximum as in figure 49. Hence A will generate peak voltage, while B generates 70 percent of peak voltage.

Here's how to add these two voltages with vectors. The peak voltage of the generator is 10 volts, so lay

off a line OA, in figure 49, 1 inch long to represent 10 volts. Your vector scale is 1 inch = 10 volts.

Then lay off a line OB at an angle of 30° to OA, but make OB only ¾ inch long to indicate 7.5 volts. Next, build up a parallelogram by making AC equal and parallel to OB, and BC equal and parallel to OA. Then draw the diagonal OC. Measure its length,

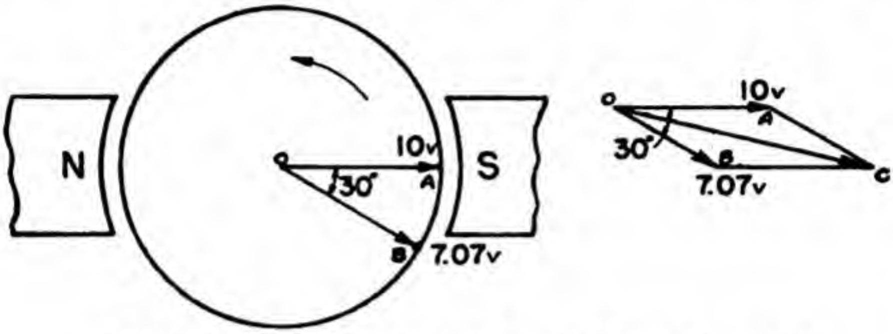


Figure 49.—Two-loop armature and its vector diagram.

which turns out to be 16⅞ inches, or 16.88 volts. And that gives you the resultant emf of the two voltages.

OTHER VECTOR TRICKS

Here are some other things you can do with vectors. You can subtract one value from another with vectors, as in figure 50. You want to subtract vector OE from vector OD. So you reverse the direction of OE

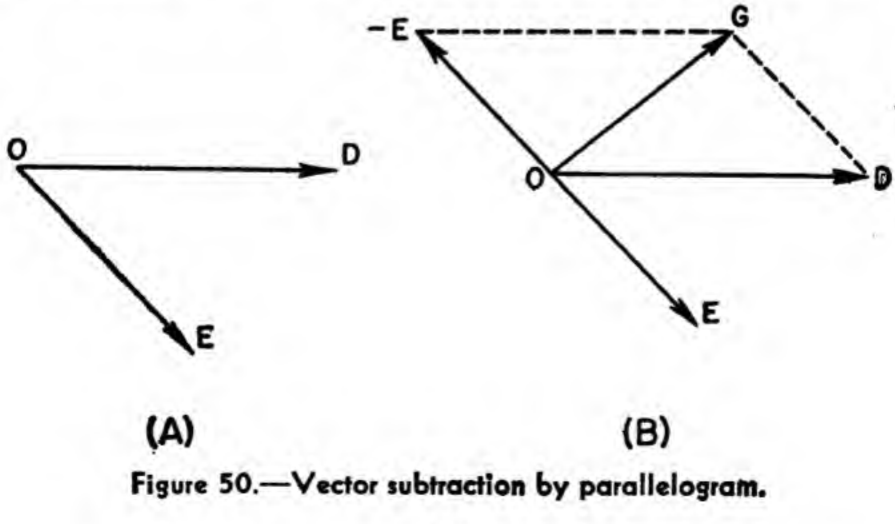


Figure 50.—Vector subtraction by parallelogram.

to get MINUS OE, and then construct the parallelogram. The resultant vector, OG, gives you the scale and direction of the difference of the two vectors.

And here's a short-cut. You don't need to construct the parallelogram each time to get the resultant vector. Just make a TRIANGLE, as in figure 51, and your resultant will give you the length and direc-

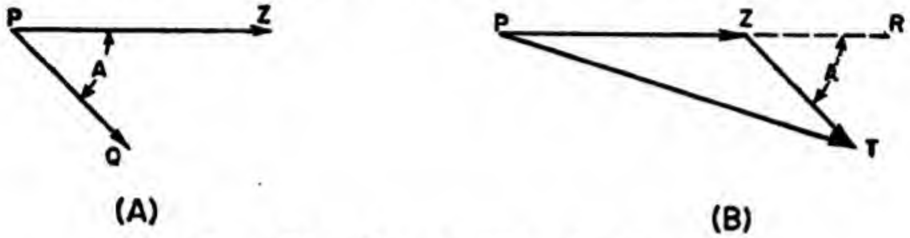


Figure 51.—Vector addition by triangles.

tion of the vector. Here's how the triangle method works.

Lay off one vector, PZ. Then from the arrowhead of PZ, lay off your second vector ZT, equal to PQ, making the correct angle A between PR and ZT. Now connect P to T, and PT is the resultant vector of the addition of vectors PZ and PQ.

And here's the method for SUBTRACTING vectors by triangles. Look at figure 52. You want to sub-

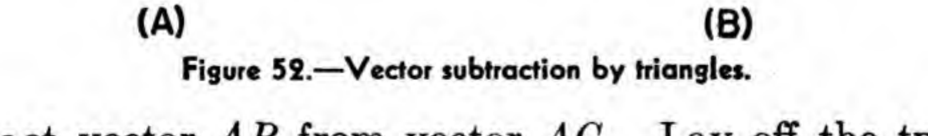


Figure 52.—Vector subtraction by triangles.

tract vector AB from vector AC. Lay off the two vectors AB and AC in the proper directions and to the proper scale. Then, you say to yourself "Take AB FROM AC" and you move out along the first vector or AB to the arrowhead. Then draw a line FROM that arrowhead to the arrowhead of the second

vector AC. The resultant BC is the vector difference of AC-BC. But—

If you were subtracting AC from AB, you'd move out AC to the arrowhead, then draw a vector FROM C to B. Your resultant arrow would now be CB, not BC as before. Direction of the resultant has been REVERSED.

So much for the theory of vectors. Next, you'll see how much they can simplify your analysis of a. c.

VECTOR ANALYSIS OF A. C.

In figure 53, you see two alternating currents, I_1 and I_2, plotted as sine waves. I_1 has an effective cur-

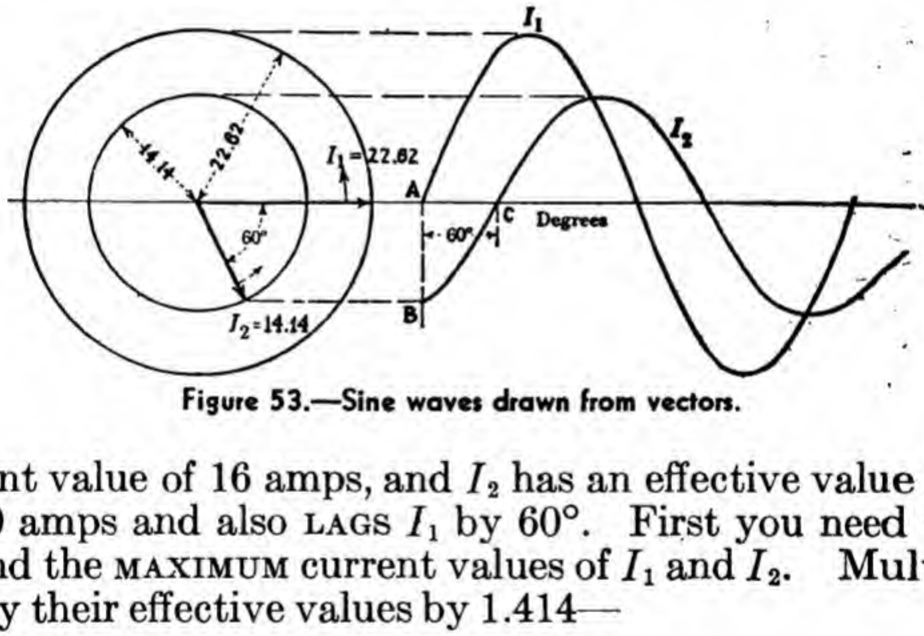


Figure 53.—Sine waves drawn from vectors.

rent value of 16 amps, and I_2 has an effective value of 10 amps and also LAGS I_1 by 60°. First you need to find the MAXIMUM current values of I_1 and I_2. Multiply their effective values by 1.414—

Then I_1 max$=16\times1.414=22.62$ amps.
And I_2 max$=10\times1.414=14.14$ amps.

Next, draw two circles, one with a radius to a scale of 22.62, and the other with a radius to a scale of 14.14. Now, remembering that I_2 lags I_1 by 60°, you are ready to rotate the two radii COUNTERCLOCKWISE, and project their lengths horizontally across to produce two sine waves, I_1 and I_2 in figure 53. You'll see that these sine waves automatically fall 60° out of

phase, since you have laid out the vectors 60° out of phase. Always remember to ROTATE YOUR VECTORS COUNTERCLOCKWISE. Electrical engineers all over the world have agreed to use counterclockwise rotation so that their diagrams would be uniform and easy to understand.

Next, suppose you want to feed the two currents I_1 and I_2 into a line. You must know what current flows in that line at various instants. If they were d. c., you'd have no trouble. You'd just add 10 to 16, and get a total of 26 amps. But it's not so easy with a. c. I_1 is zero when I_2 is -11.3 amps, and so on around to the instant when I_1 is maximum 22.62 amps and I_2 is building up towards its maximum. Now here's where you'll really be glad you know about VECTOR ADDITION.

You could labor through and plot the two sine curves I_1 and I_2, and then struggle with measuring off their respective values at various instants. And eventually you'd come up with a curve that looks somewhat like I_3 in figure 54.

Want to do it the easy way? All right, use the parallelogram method you learned earlier in this chapter. In figure 54 (*B*), you have an enlarged sketch of the parallelogram that is shown in figure 54 (*A*). See what you do? Lay off line *AB* horizontally and to a scale of 22.62 amps for I_1. Then lay off *AC*, making a LAG angle of 60° with *AB*, and to a scale of 14.14 amps for I_2. Next, construct the parallelogram *ABDC* around the vectors *AB* and *AC*. Finally, draw the diagonal *AD*, scale it off, and you find that—

$$I_1+I_2=I_3=32.19 \text{ amps, maximum current for } I_3$$

You also find automatically that I_1 leads I_3 by angle θ, on figure 54 (*B*).

Next draw a third circle of radius 32.19 amps to scale around the circles I_1 and I_2 on figure 54 (*A*),

and you can readily construct the sine curve for I_3 as your alternating current, I_1 and I_2, vary from maximum positive through zero to maximum negative, and back again.

And now since you know that the EFFECTIVE values of I_1 and I_2 are 16 and 10 amps., respectively,

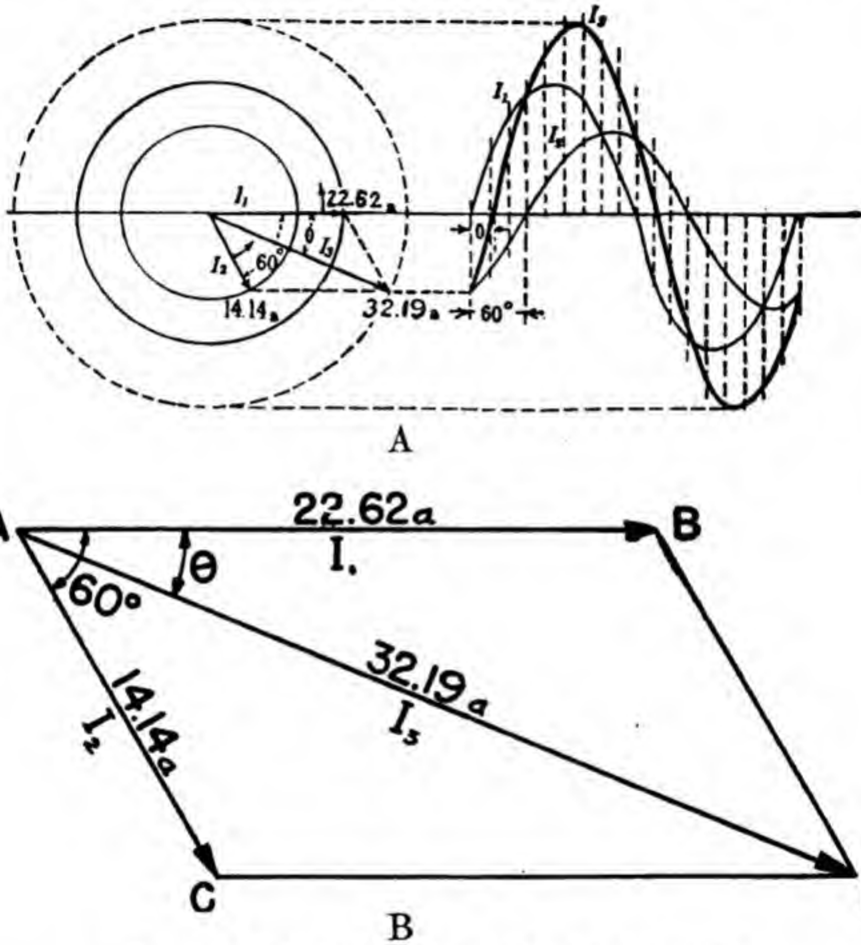


Figure 54.—Vector addition of two a-c currents.

you'll want to know the EFFECTIVE value of I_3. Just multiply the MAXIMUM value of I_3, which you found by vector addition to be 32.19 amps., by 0.707—

$$I_3 \text{ eff.} = I_3 \text{ max.} \times 0.707 = 32.19 \times 0.707 = 22.76 \text{ amps.}$$

Of course, you can also solve the problem of the EFFECTIVE current of I_3 vectorially, without bothering

with the MAXIMUM currents. Lay off a horizontal line to represent I_1 eff. to a scale of 16 amps. Then lay off at a LAG angle of 60° a second line to represent I_2 eff. Construct a parallelogram around I_1 and I_2. The diagonal will give you I_3, which you can measure to discover that I_3 eff. = 22.76 amps.

REMEMBER THIS!! You must combine ALTERNATING voltages and currents by VECTORS. There is no other way to do it.

A PROBLEM IN A. C.

Got time for a problem to test your brains on vectors?

PROBLEM: You have an a-c generator, A, which produces an effective current of 100 amperes. You have a second a-c generator, B, producing an effective current of 60 amperes, and operating 45° out of phase, lagging, with the first generator. If you feed the output of these two generators into a line, what effective current will you get from the line?

* * * *

SOLUTION: Figure 55 gives you the vector diagram and sine curves.

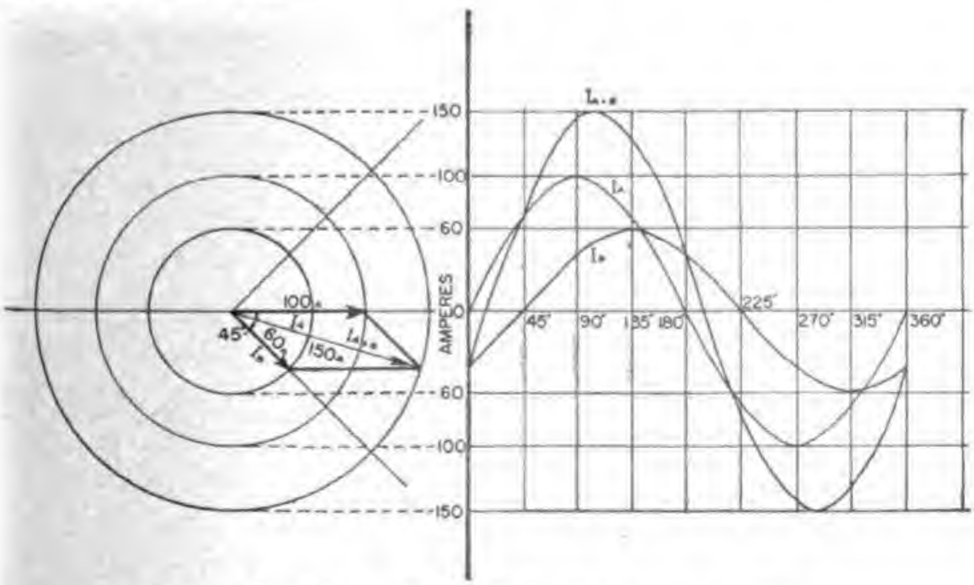


Figure 55.—The problem of the two a-c generators.

A-C POWER

You remember that d-c power is the product of voltage and current. The same formula—

$$P=EI$$

can be used with the INSTANTANEOUS values of E and I for a. c. to obtain INSTANTANEOUS POWER, but you do not necessarily get the AVERAGE power if you multiply the EFFECTIVE current and EFFECTIVE voltage together.

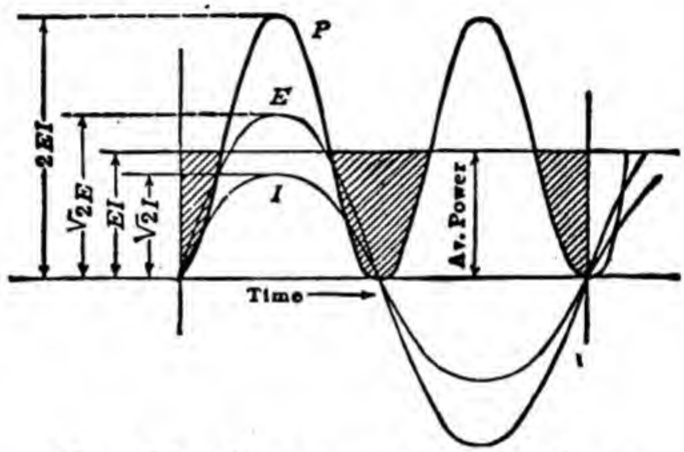


Figure 56.—Power curve; E and I in phase.

VOLTAGE AND CURRENT IN PHASE

Suppose you had voltage E in phase with current I, as in figure 56. In the first half of the cycle, E and I are both positive. So $P_{\text{instantaneous}}$ is positive, reaching its peak along with $E_{\text{inst.}}$ and $I_{\text{inst.}}$ inst., which are in phase. Then the curves of instantaneous values for E, I, and P all hit zero together. In the next alternation, both E and I go negative. But multiplying $-E$ by $-I$ gives you a $+P$, so the power curve rolls up again to a maximum POSITIVE at the same time instant that E and I reach a maximum NEGATIVE. As long as E and I are in phase, the power curve P will always be POSITIVE and will also be a sine curve with TWICE the frequency of the E and I curves.

The PEAK of the power curve P can be found by using the formula—

$$P_{max}=(\sqrt{2}\times E_{eff})(\sqrt{2}\times I_{eff})=2E_{eff}\times I_{eff}$$

where E_{eff} and I_{eff} are the EFFECTIVE values of voltage and current.

You can see that if you run a line through the power sine curve at a distance EI above the zero line, the peaks of the curves above this line EI will just properly fill in the shaded valleys between the loops of the power curves in figure 56. Then if you take the AVERAGE HEIGHT of the power loops as being EI, marked on figure 56, you'll be able to solve problems of a. c. in phase. For instance—

THIS PROBLEM

You have a string of regular Mazda lamps. The whole string draws 30 amps at 110 volts, 60 cycles. How much POWER do the lamps use? This type of load is IN PHASE.

Use the formula—

$$P_{eff}=E_{eff}\times I_{eff}=110\times 30=3{,}300 \text{ watts.} \quad (Ans.)$$

See how you solve a. c. IN PHASE just as you solve d. c.? BUT—a. c. OUT of phase is something else!

A. C. OUT OF PHASE

Now look at a case where a-c voltage LEADS the current by a $\theta°$ phase angle. You have the diagram

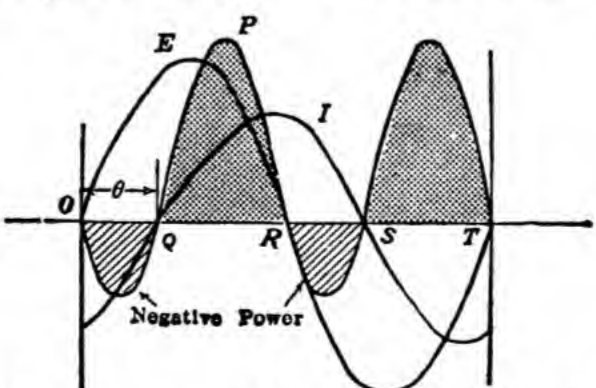


Figure 57.—Power curve. E is Θ° out of phase with I.

in figure 57. The phase angle, $\theta°$, is more than 0° and less than 90°. P is the power curve.

At points O, R, and T, VOLTAGE becomes zero, while at points Q and S, CURRENT is zero. Because of this zero value in your multiplication, the value of power curve P is zero at ALL these points. Between points O–Q and R–S, voltage is positive when current is negative—or voltage is negative when current is positive, so your power curve is NEGATIVE between these points. But between Q–R and S–T, voltage and current are both positive, or both negative, at the same time, so your power curve P rises to POSITIVE loops.

You can easily see that the positive power loops—shown dotted— have greater area than the negative power loops—shown cross-shaded. And your average power is a positive quantity, but is less than $E \times I$. You can use this information to make up a formula—

$$P_{av} = EI \text{ cosine } \theta°$$

If you know the phase angle, $\theta°$, you can find out the cosine of $\theta°$ in any trigonometry book. P gives you true power or true watts, and EI gives you the apparent watts or volt-amperes. The cosine θ, usually written "cos θ" gives you the POWER FACTOR of the machine or transformer.

Suppose you need to know the power factor of an a-c machine or a transformer. You can get it thus—

$$\text{Power Factor or P. F.} = \frac{P}{EI} = \cos \theta$$

Remember, though—you can never have a P. F. that is GREATER than 1, or UNITY, as the mathematics men call "one". The best phase angle you can get is 0°, when E and I are in phase, and the cosine of 0° is 1.000. So don't try to get a P. F. bigger than 1.0, or you'll have a weird kind of generator.

A PROBLEM

Suppose you have an a-c generator with voltage leading current by 37°. What's the P. F.?

$$P.\ F. = \cos \theta = \cos 37° = 0.80$$

so your generator has an 80 percent power factor.

RESISTANCE IN A-C CIRCUIT

An a-c circuit that contains only RESISTANCE can be treated exactly like a d-c circuit. That is, the formula for power is the same—

$$P = EI = I^2R$$

A vector diagram, figure 58, shows that $E = IR$, and that the IR drop or voltage drop is equal to the voltage E, and is in phase with the current I.

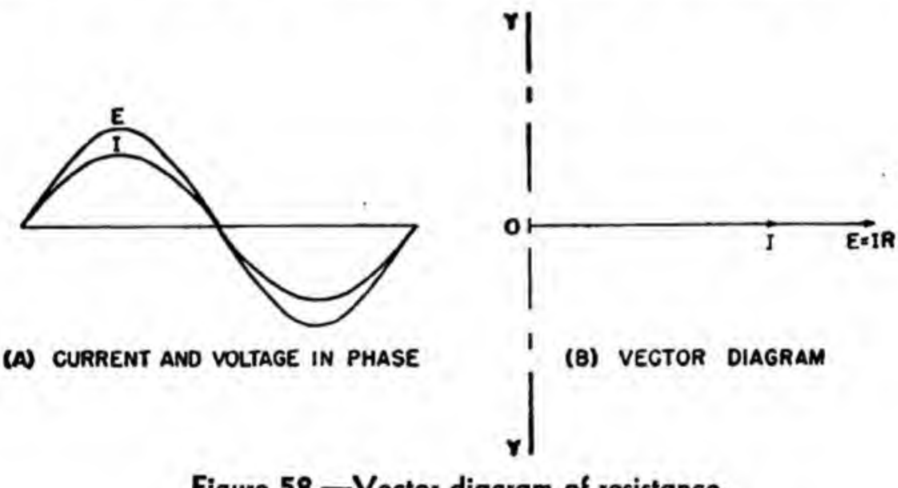


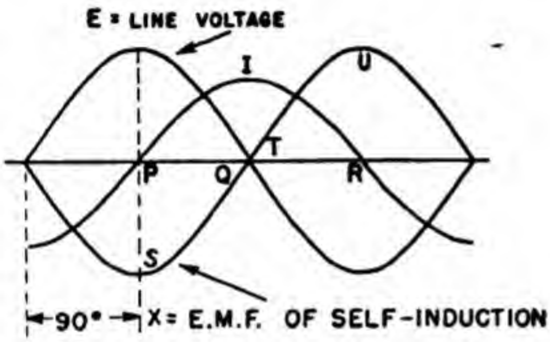
Figure 58.—Vector diagram of resistance.

INDUCTANCE IN A-C CIRCUIT

You remember what INDUCTANCE is—the opposition of a current to any change, whether large or small. When you handle d. c., inductance is of little importance, since current changes occur only infrequently, as when the circuit is opened or closed. But a. c. changes direction 120 times a second or even

more frequently. Hence inductance becomes of great importance in the study of a. c.

Look at figure 59 (*A*), which shows the voltage curve, current curve, and inductance curve for an a-c circuit containing pure inductance with no resistance. Notice that the current curve, *I*, is at maximum rate of change at point *P*, where the current changes from negative to positive. So that's where you'd expect MAXIMUM INDUCTANCE or resistance to change. And since the current is changing from negative to positive, you'd expect the induced emf to



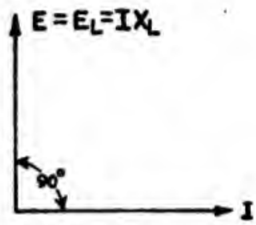


Figure 59.—Current and voltage relationship in inductive circuit.

be maximum negative. All right, put on point *S* at the same instant of time as point P, and S maximum negative. Next, at time *Q*, the current curve reaches its peak, and levels off for a split-second, its rate of change being zero. So you'd expect the inductance at that instant to be zero, which it is. Your inductance curve will go through zero at time instant *Q*.

Next, the current undergoes a maximum change from positive to negative at instant *R*, and so you'd expect the inductance to reach a maximum positive value at that instant to oppose the maximum rate of change of curve *I* from positive to negative.

You can now draw a sine curve for the values of inductance opposing the a. c. The inductance curve will have the same FREQUENCY as the cur-

rent curve, but will be 90° out of phase, LAGGING. The current curve LEADS the inductance curve by 90°.

The LINE VOLTAGE, E, has to overcome the inductance emf, or no current will flow in the a-c circuit. Hence, curve E of line voltage will be equal in value to curve X of inductance, but will oppose it in order to cancel it out. Thus, in figure 59 (A) curve E is maximum POSITIVE at the instant that curve X of inductance is maximum NEGATIVE. Both are zero together, and E is maximum negative when X is maximum positive. Curve E is 180° out of phase with curve X.

Now you can see that your imaginary circuit which contains only inductance, with no resistance has its voltage LEADING the current by 90°. So you can draw the vector diagram of figure 59 (**B**), with arrow E leading arrow I by 90°.

The symbol for inductance is L, and the unit of inductance is the HENRY.

In this imaginary circuit having inductance only, the current is directly proportional to voltage, and is inversely proportioned to frequency and self-inductance. A formula shows this—

$$I=\frac{E}{2\pi fL}$$

where f is the frequency, and L is the self-inductance.

The choking effect or the resistance to the flow offered by inductance is represented in the formula by $2\pi fL$, and is called the INDUCTANCE REACTANCE of the circuit. The symbol for inductive reactance is X_L, and its unit is the OHM. Thus the voltage impressed on the circuit is—

$$E=2\pi fLI=IX_L$$

Here's a problem—

A pure inductance of 0.3 henry is connected across a 110-volt, 60-cycle feeder. How much current flows?

$$I=\frac{E}{X_L}=\frac{E}{2\pi fL}=\frac{110}{2\pi 60\times 0.3}=0.973 \text{ amp.} \quad \text{(Ans.)}$$

CAPACITANCE IN A-C CIRCUIT

You remember how a condenser works in a d-c circuit. When you close the circuit, current flows for a brief instant and electrons rush into one plate

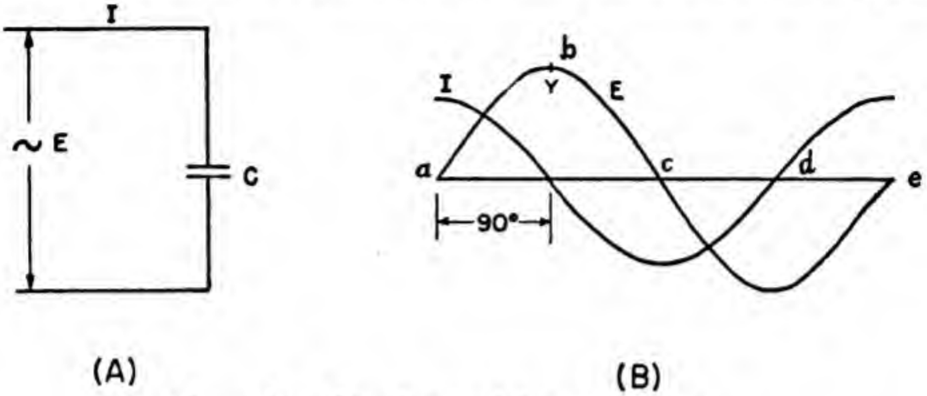


Figure 60.—Circuit containing capacitance.

of the condenser and out of the other plate until the condenser is charged to the line potential. Then, while the voltage remains constant, there is no further current flow. Open the circuit and replace the voltage source with a load. Current flows—electrons moving away from one plate, through the load, and toward the other plate of the condenser. But when you feed a. c. to a condenser, you are charging and discharging the condenser many times a second, and condenser behavior becomes very important.

In figure 60 (*A*), you see a circuit with an a-c voltage impressed across a condenser *C*. At instant *a*, the a-c voltage is crossing the zero voltage line and rising to a positive value. The condenser is being charged in such a way that, let us say, the upper plate becomes positive and the lower plate negative. Current flows and the charge on the condenser increases as long as the line voltage is increasing.

At instant *b*, however, the line voltage starts dropping back to zero. From *b* to *c*, line voltage continues to drop, so that the charge on the condenser, being greater than the line voltage, forces electrons to flow away from the lower plate of the condenser and into the upper plate. Since the current flow has now

reversed its direction, the current is shown in figure 60 (*B*) as being NEGATIVE. Its curve drops below the zero line of the sine wave diagram, to become maximum NEGATIVE at instant *c*.

At instant *c*, the line voltage crosses the zero line and becomes NEGATIVE, dropping toward maximum negative. This voltage again charges the condenser, but this time the upper plate of the condenser is negative and the lower plate is positive. Hence, the current curve is still on the NEGATIVE side of the zero axis, but is approaching zero value.

Current becomes zero at instant *d*, when the line voltage is momentarily stationary at maximum NEGATIVE, before starting back to zero. At instant *d*, voltage starts back to zero, so that the charge on the condenser soon becomes greater than the line voltage and current starts to flow—with electrons streaming away from the upper plate of the condenser, through the circuit, toward the lower plate. Thus, the current flow has changed direction and is shown in figure 60 (*B*) as being POSITIVE. The current becomes maximum positive at instant *e*, as the line voltage becomes zero.

You will see that current wave *I* LEADS voltage wave *E* by 90°. You can now draw the vector diagram, shown in figure 61.

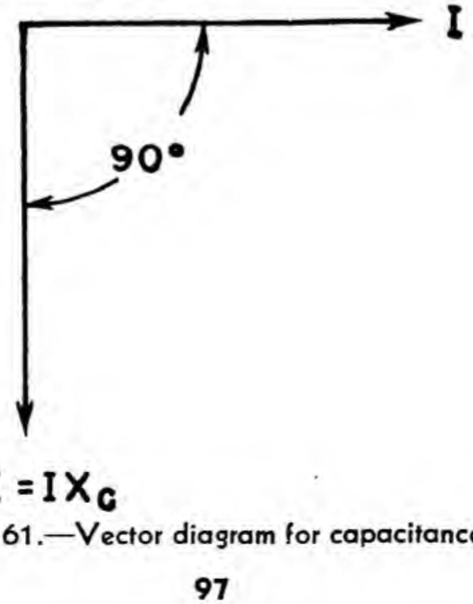


Figure 61.—Vector diagram for capacitance.

Alternating current does not actually FLOW through the insulation of the condenser, of course, but the condenser is alternately charged and discharged, making a quantity of electricity flow into the positive plate and then out again, and so on. This alternating charging and discharging of the condenser plates makes up the a. c. The greater the number of alternations per second, the more current that is charged and discharged each second by the condenser, and the greater is the flow of current. Therefore the current through a condenser is proportional to the frequency of the voltage.

And so, we can write a formula—

$$I = E(2\pi f C)$$

where I is effective current, E is effective voltage, f is the frequency, and C is the capacitance of the condenser in FARADS.

And it is perfectly good mathematics to invert that equation and make—

$$I = E(2\pi f C) = \frac{E}{\frac{1}{2\pi f C}}$$

The fraction, $\frac{1}{2\pi f C}$ is the CAPACITIVE REACTANCE of a circuit and is expressed by—

$$\frac{1}{2\pi f C} = X_C, \text{ in OHMS}$$

$$I = \frac{E}{X_C} \text{ and } E = IX_C$$

RESISTANCE AND INDUCTANCE IN A-C CIRCUIT

In figure 62, you have the diagram for a circuit containing a resistance R and an inductive reactance X_L. An a-c voltage of E volts and f cycles is impressed on the circuit, and I amperes flow. You want to find out all about the circuit.

Draw a vector diagram, figure 63. Lay off I to a

convenient scale and in a convenient position. Next lay off the voltage across the resistance. Remember you found out that the voltage, E_R, across a resistance is IN PHASE with the current. Then make your E_R vector lie along vector I, and to scale, as in figure 63A.

You also will remember reading that the voltage, E, across an inductance is 90° out of phase, leading,

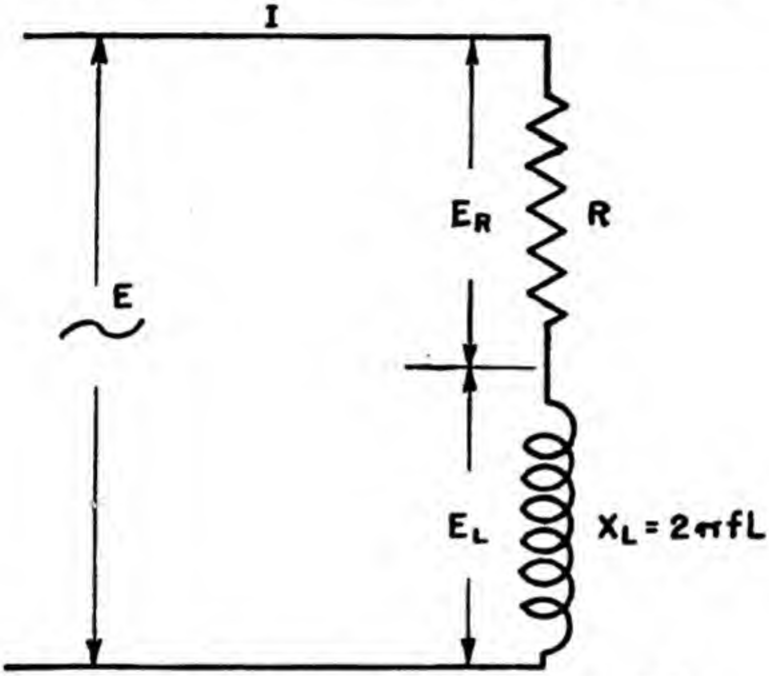


Figure 62.—Resistance and inductance in series.

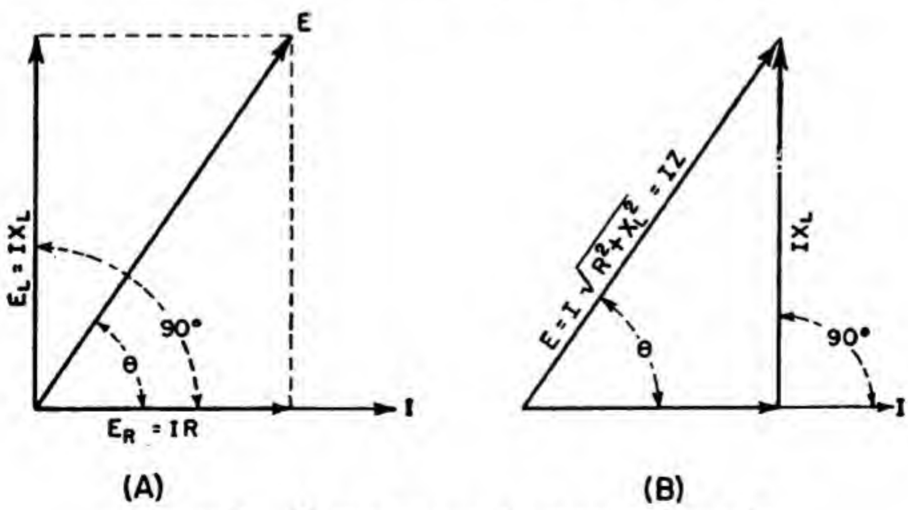


Figure 63.—Vector diagram for circuit in figure 62.

with current through the inductance. So lay off E_L leading I by 90°, and to scale. Now if you construct your parallelogram around E_R and E_L, you'll discover the total voltage across the resistance and the inductance. The resultant vector, E, in figure 63 gives you the value and direction of E.

RUN THROUGH THIS PROBLEM

You have a 110-volt, 60-cycle voltage on a circuit that includes a 100-ohm resistance and a 0.1-henry inductance. You want to know: (*a*) Impedance of the circuit; (*b*) value of current flow; (*c*) voltage across resistance; (*d*) voltage across inductance; (*e*) angle of lead of voltage and current. Draw the vector diagram.

First, (*a*) $Z=\sqrt{R^2+(2\pi fL)^2}$

$$=\sqrt{100^2+(2\pi\times 60\times 0.1)^2}$$

$$=\sqrt{10{,}000+1{,}420}=\sqrt{11{,}420}$$

$$=107 \text{ ohms. (Ans.)}$$

Next, (*b*) $I=\frac{E}{Z}=\frac{110}{107}=1.03$ amps. (Ans.)

Then, (*c*) $E_R=IR=1.03\times 100=103$ v. (Ans.)

And, (*d*) $E_L=IX_L=I(2\pi fL)$

$$=1.03(2\pi\times 60\times 0.1)=38.8 \text{ v. (Ans.)}$$

So, (*e*) $\text{Tan } \theta=\frac{X_L}{R}=\frac{2\pi\times 60\times 0.1}{100}=0.376$

and $\theta=20.6°$. (Ans.)

And the vector diagram is in figure 64.

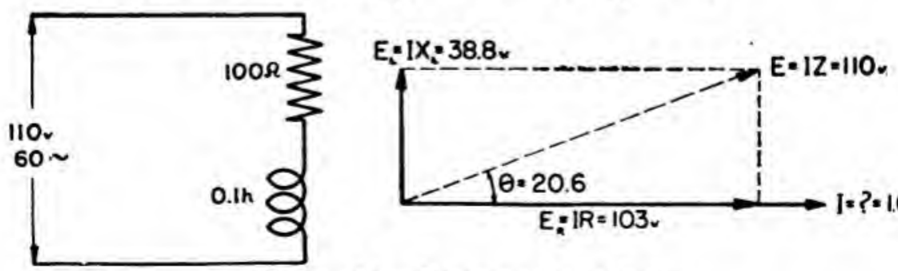


Figure 64.—Diagram for problem.

POWER

No power is used up by the pure inductance in a circuit. Here's why. As the current increases from zero to a maximum value, it stores up energy in the magnetic field of the inductance. Then as the current decreases from maximum to zero, all this stored energy is released back into the circuit.

ALL the power used up in a circuit is expended in resistance, so that—

$$P = I(IR) = I^2R$$

and since from figure 64, by trigonometry you find that you can substitute, and get—

$$IR = E \cos \theta$$

Earlier you saw that $\cos \theta$ is the POWER FACTOR of a circuit, so the P. F. is equal to TRUE POWER, P, divided by APPARENT POWER, EI. Then—

$$\text{P. F.} = \frac{P}{EI}$$

A POWER PROBLEM

In that problem on page 100, find out how much power is consumed and what power factor the circuit has.

$$P = I^2R = \overline{1.03}^2 \times 100 = 1.06 \times 100 = 106 \text{ watts.}$$

and $$\text{P. F.} = \frac{106}{110 \times 1.03} = 0.935 = 93\tfrac{1}{2} \text{ percent P. F.}$$

You can also find the P. F. by using—

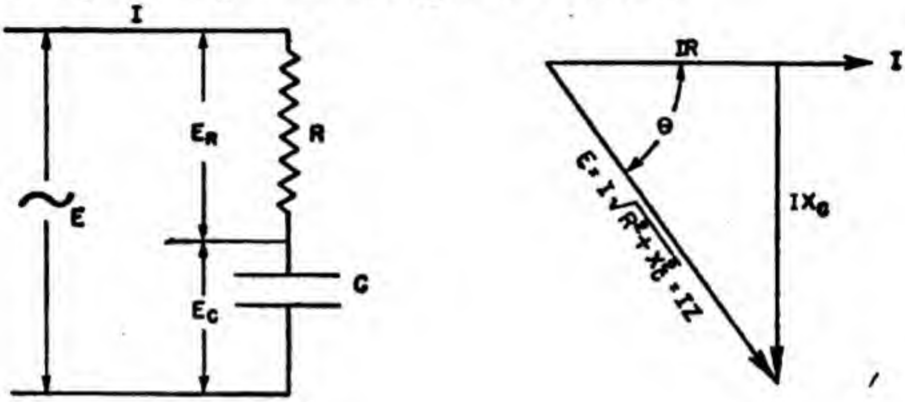
$$\text{P. F.} = \cos \theta = \cos 20.6° = 0.936 = 93\tfrac{1}{2} \text{ percent.}$$

RESISTANCE AND CAPACITANCE IN A-C CIRCUIT

In figure 65 (A), you have the diagram of a circuit containing both resistance, R, and capacitance, C, in series. An a-c voltage E is connected across this

circuit, and an alternating current I flows in the lines. What are the relations between E, I, R, and X_C?

Look at the vector diagram for this circuit in figure 65 (B). It's a triangle vector diagram for a change, not a parallelogram. Current I flows through the resistance and the condenser. So you lay off I as a vector arrow to a convenient length, and horizontally. You remember that the voltage, E_R, through a resistor is IN PHASE with the current. So you lay off $E_R=IR$ along the vector I.



(A) (B)

Figure 65.—Resistance and capacitance in series.

Now you come to the voltage, E_c, through the condenser. You've just learned that E_c must LAG the current through the condenser by 90°, so you lay off a vector 90° BEHIND IR, and measure off $E_C=IX_C$ along it. Next draw the third side of the vector triangle, which gives you the value and direction of E. Because it is the hypotenuse of a right triangle—

$$E=\sqrt{\overline{IR}^2+\overline{IX_c}^2}$$

$$=I\sqrt{R^2+\overline{X_c}^2}$$

Let $\sqrt{R^2+\overline{X_c}^2}$ be represented by Z, the impedance of the circuit. Then—

$$E=IZ$$

Or, if you want the value of current—

$$I=\frac{E}{Z}$$

Next, you can find the power used in the circuit. Since the capacitive reactance takes zero power, all the power is used by the resistance. Thus—

$$P=I^2R=I(IR)$$

Now you can find the angle of lag, θ, by this formula—

$$\cos\theta=\frac{IR}{E} \text{ or } E\cos\theta=IR$$

Then substituting—

$$P=I(E\cos\theta)=EI\cos\theta$$

Recognize that formula? It's the same formula that you had on page 101 for power in a circuit containing inductance and resistance.

To find angle θ, you use this formula—

$$\tan\theta=\frac{X_C}{R}=\frac{R}{Z}$$

Then—

$$P.\ F.=\frac{R}{Z}=\cos\theta$$

A PROBLEM WILL EXPLAIN

You have a 25 μf. condenser and a 90-ohm resistance in series in a 110-volt, 60-cycle line. What is: (*a*) Impedance of the circuit; (*b*) current in circuit; (*c*) voltage across the resistance; (*d*) voltage across the condenser; (*e*) phase angle of voltage and current; (*f*) power; (*g*) power factor?

First, $C=25\mu f.=0.000025$ farad.

Then (*a*), $Z=\sqrt{R^2+X_C^2}$,

$$\text{where } X_C=\frac{1}{2\pi fC}=\frac{1}{2\pi\times 60\times 0.000025}=106 \text{ ohms}$$

So, $Z=\sqrt{\overline{90}^2+\overline{106}^2}=139$ ohms. (Ans.)

Next, (*b*), $I=\frac{E}{Z}=\frac{110}{139}=0.791$ amp. (Ans.)

And, (*c*), $E_R=IR=0.791\times 90=71.3$ volts. (Ans.)

And, (*d*), $E_C=IX_C=0.791\times 106=84$ volts. (Ans.)

So (*e*), $Tan\ \theta=\frac{X_C}{R}=\frac{106}{90}=1.75=tan\ 60.3°$

Then (*f*), $P=I^2R=(0.791)^2\times 90=56.25$ watts. (Ans.)

Finally (*g*), $P.\ F.=\frac{R}{Z}=\frac{90}{139}=0.64=64\%$ (Ans.)

RESISTANCE, CAPACITANCE, AND INDUCTANCE

And now we come to a REAL circuit—an a-c circuit with resistance *R*, capacitance *C*, and inductance *L*, all in series, and shown in figure 66. You put

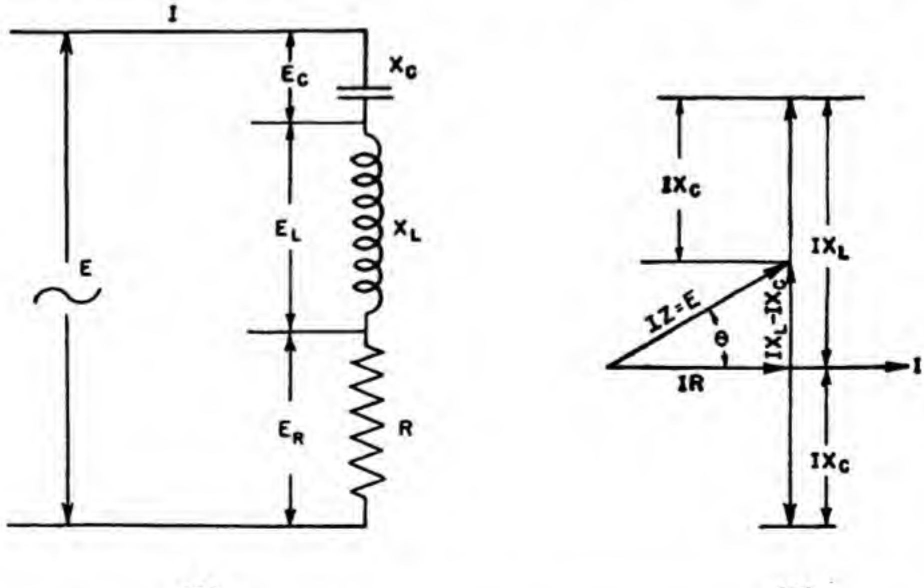


Figure 66.—Circuit containing resistance, capacitance, and inductance.

a voltage E of frequency f across this circuit, and current I flows. Next, find out how E, I, R, and C and L fit together in the circuit.

This is a series circuit, therefore current I is the same throughout the circuit. You can start constructing the vector diagram in figure 66 by laying off the arrow for I horizontally. The voltage E_R through the resistance is IN PHASE with current I, and is equal to IR. So you can lay off IR to scale along vector I.

Voltage E_L through the inductance LEADS the current I by 90° so the vector for $E_L=IX_L$ is laid off at right angles to I, and to scale. Voltage E_C through the capacitance LAGS current by 90°, and $E_C=IX_C$. You lay off the vector for IX_C at right angles, lagging I, and to scale.

Now you can see that E_L and E_C oppose each other. Also, since you've drawn your vectors to scale, you can readily see that IX_L is greater than IX_C. Now you can subtract IX_C directly from IX_L, as shown in the upper half of the vector diagram of figure 66 (B).

You can now determine the line voltage E by a vector addition of the three voltages—IX_L, IX_C, and IR. This line voltage will be the hypotenuse of a right triangle, the other two sides of which are IR and (IX_L-IX_C). By drawing this hypotenuse, you get vector E.

You now see that—

$$E=\sqrt{\overline{IR}^2+(IX_L-IX_C)^2}$$

since the hypotenuse of a right triangle is the square root of the sum of the squares of the other two sides.

Then—

$$E=I\sqrt{R^2+(X_L-X_C)^2}$$

And—

$$I=\frac{E}{\sqrt{R^2+(X_L-X_C)^2}}$$

Let—

$$\sqrt{R^2+(X_L-X_C)^2}=Z$$

So—

$$I=\frac{E}{Z}, \text{ or } E=IZ$$

is the equation for a series a-c circuit which is STEADY at a voltage and a current.

You can find the PHASE ANGLE θ by—

$$\tan\theta=\frac{X_L-X_C}{R}$$

If X_L is greater than X_C tan θ is POSITIVE, angle θ is positive, and I LAGS E, as in figure 67. But if X_L is LESS than X_C, tan θ is NEGATIVE, angle θ is negative, and I LEADS E.

The power factor is

$$\cos\theta=\frac{R}{Z}$$

PERHAPS A PROBLEM WILL HELP

You have a circuit, shown in figure 67, with a 30-ohm resistance, a 20 μf. capacitance, and a 0.25-henry inductance, all in series. Voltage across the circuit is 110 volts, 60 cycles.

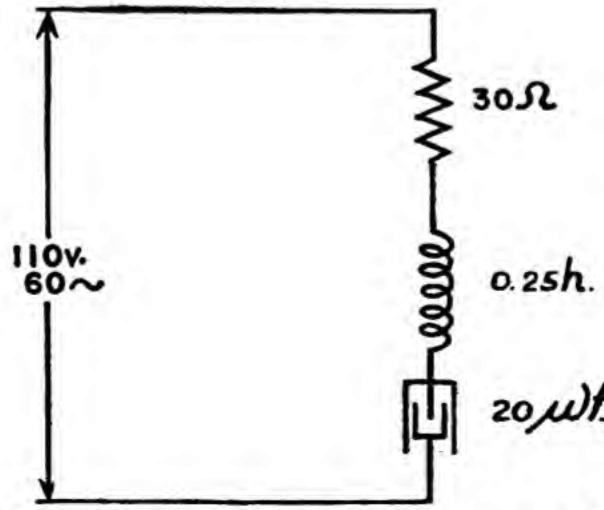


Figure 67.—Circuit containing resistance, inductance and capacitance.

Find out the following about this circuit: (*a*) impedance; (*b*) current in the circuit; (*c*) voltage across the resistance; (*d*) voltage across the inductance; (*e*) voltage across the capacitance; (*f*) power consumed by the circuit; (*g*) phase angle; (*h*) power factor; (*i*) vector diagram.

First, find X_C and X_L—

$$X_C=\frac{1}{2\pi fC}=\frac{1}{2\pi 60\times 20\mu}=\frac{1}{2\pi 60\times 0.000020}=\frac{1}{0.00753}=133\ \Omega$$

$$X_L=2\pi fL=2\pi 60\times 0.25=94.1 \text{ ohms}$$

Now, (*a*) $Z=\sqrt{R^2+(X_L-X_C)^2}=\sqrt{30^2+(94.1-133)^2}$
$=\sqrt{30^2+(-38.9)^2}$
$=\sqrt{900+1510}=\sqrt{2410}=49.1$ ohms. (Ans.)

And, (*b*) $I=\frac{E}{Z}=\frac{110}{49.1}=2.24$ amps. (Ans.)

Next, (*c*) $E_R=IR=2.24\times 30=67.3$ volts. (Ans.)

Then, (*d*) $E_L=IX_L=2.24\times 94.1=211$ volts. (Ans.)

And, (*e*) $E_C=IX_C=2.24\times 133=298$ volts. (Ans.)

So, (*f*) $P=I^2R=(2.24)^2\times 30=151.5$ watts. (Ans.)

Next, (*g*) $\tan\theta=\frac{X_L-X_C}{R}=\frac{94.1-133}{30}=\frac{-38.9}{30}=-1.295$

and $\theta=-52°20'$. (Ans.)

Since θ is a MINUS angle, the current LEADS the voltage.

Finally, (*h*) $\cos\theta=\frac{R}{\sqrt{R^2+(X_L-X_C)^2}}$

$$=\frac{30}{\sqrt{(30)^2+(94.1-133)^2}}=\frac{30}{\sqrt{(30)^2+(-38.9)^2}}$$

$$=\frac{30}{\sqrt{900+1510}}=\frac{30}{\sqrt{2410}}=\frac{30}{49.1}=0.61$$

So P. F. $=\cos\theta=0.61=61$ percent.

(i) The vector diagram for this circuit is figure 68. Notice that the voltage E_C across the capacitance is much larger than the line voltage E. You couldn't have this condition in a d-c circuit, since the voltage

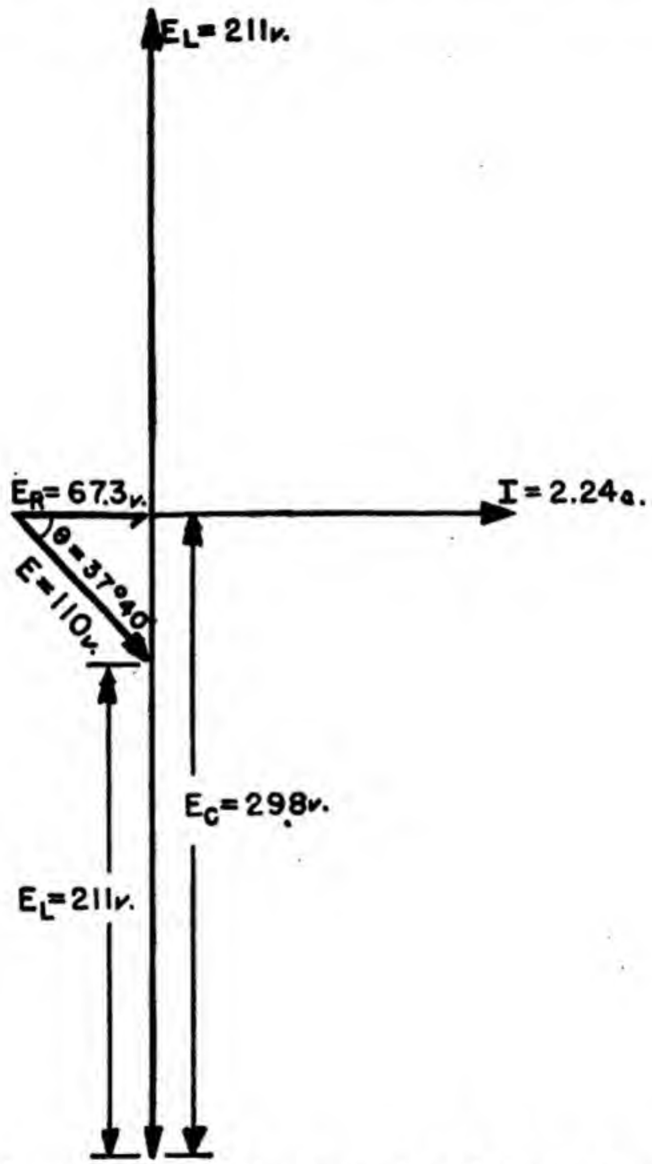


Figure 68.—Vector diagram of circuit containing inductance, resistance, and capacitance.

across any part of the d-c circuit cannot be greater than the line voltage.

However, this condition is perfectly normal for an a-c circuit, since the capacitance voltage E_C and

the inductance voltage E_L are in direct opposition to each other. Both may be large, but their DIFFERENCE must not exceed line voltage.

RESONANCE IN A SERIES CIRCUIT

You'll remember that the general formula for current through a circuit is—

$$I=\frac{E}{\sqrt{R^2+\left(2\pi fL-\frac{1}{2\pi fC}\right)^2}}$$

If the values of voltage E and resistance R are fixed, you'll find that the current through the circuit will be maximum when the UNSHADED portion of this equation, in figure 69, is equal to zero.

$$I=\frac{E}{\sqrt{R^2+\left(2\pi fL-\frac{1}{2\pi fC}\right)^2}}$$

Figure 69.

Thus, when $\left(2\,\pi fL-\frac{1}{2\pi fC}\right)$ is equal to zero, this equation becomes—

$$I=\frac{E}{\sqrt{R^2+O}}=\frac{E}{R}$$

which is OHM'S LAW. Then, under these conditions—

$$2\pi fL=\frac{1}{2\pi fC}$$

Multiply each side by I, and—

$$2\pi fLI=\frac{I}{2\pi fC}$$

so that voltage across the inductance is now equal to voltage across the capacitance. Since voltage across

the inductance LEADS the current by 90°, and voltage across the CAPACITANCE lags the current by 90°, the two voltages, $2\pi fLI$ and $\frac{I}{2\pi fC}$ are 180° apart, or directly opposite each other. Look at the vector diagram in figure 70. See how the vector for inductance voltage is equal and opposite to capacitance voltage under these conditions.

When these conditions exist, the series circuit is in RESONANCE, and the current I is IN PHASE with the line voltage E. Power P is equal to EI.

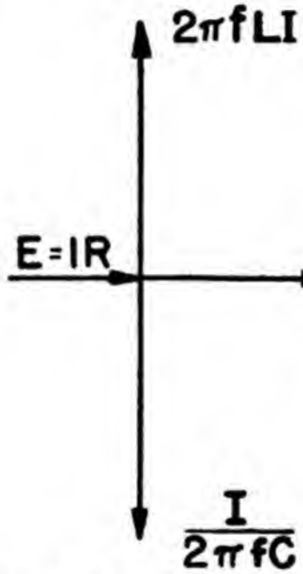


Figure 70.—Vector diagram.

You can now find the FREQUENCY at which the circuit is RESONANT by making—

$$2\pi fL-\frac{1}{2\pi fC}=0$$

when L and C have fixed values.
Then—

$$f=\frac{1}{2\pi\sqrt{LC}}$$

which is also called the NATURAL FREQUENCY of the circuit. This is the frequency at which the

circuit would oscillate if placed in an oscillator circuit.

REMEMBER—THE CURRENT IS MAXIMUM WHEN THE SERIES CIRCUIT IS IN RESONANCE.

RESONANCE CHARACTERISTICS OF SERIES CIRCUIT

If the frequency f in a circuit is fixed at a certain number of cycles, you can get numberless combinations of inductance and capacitance to give the circuit resonance. As long as LC remains constant, you can vary the values of L and C to get hundreds of combinations. To explain simply, suppose you want—

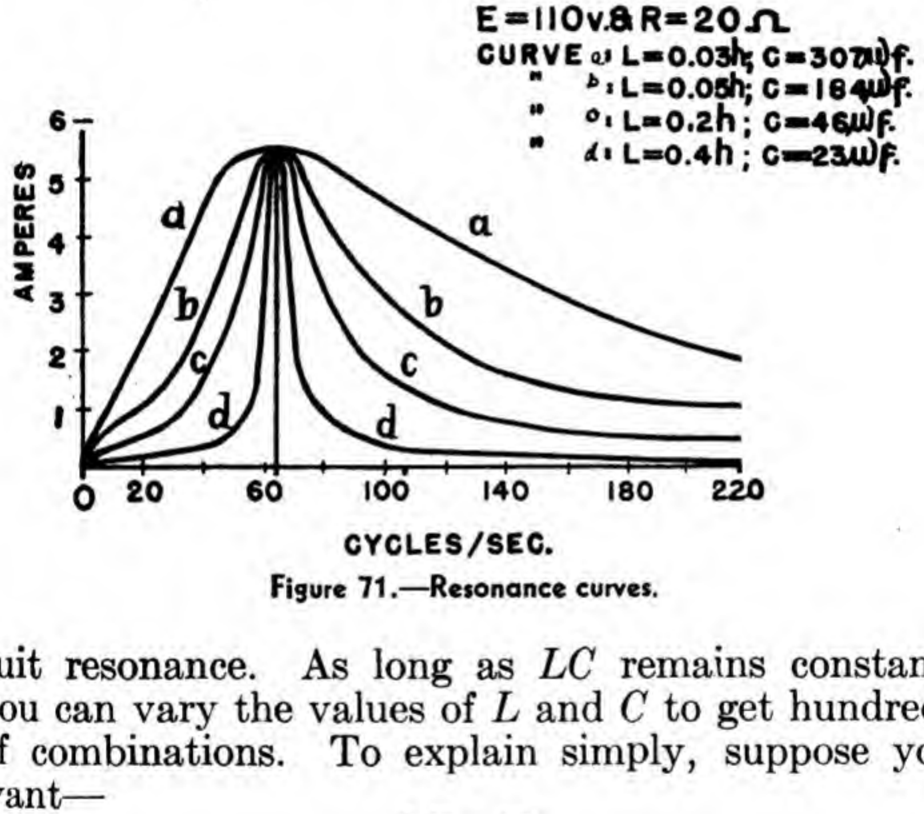


Figure 71.—Resonance curves.

$$LC = 12$$

You can get 12 by multiplying 4×3, 6×2, 1×12, 0.5×24, 0.1×120, and so on, through many combinations.

However, the characteristics of the current vary according to the relation of the inductance L to capacitance C. Look at figure 71 to see what we mean.

The circuit has a voltage E of 110 volts across it, the resistance is 2 ohms, and you tune the circuit first to 60 cycles frequency by making the inductance $L = 0.03$ henry and the capacitance $C = 307\mu f$, or microfarads. You see the variation of current I with frequency variations charted by curve *a*. The current at zero frequency is zero amperes, since a current of zero frequency is a direct current, and the condenser gives an open circuit on d. c.

You've adjusted L and C originally to make the current a maximum when the frequency is 60 cycles. You can now see from the values of L and C for the four curves in figure 71 that as inductance L is increased and capacitance C is decreased to keep LC constant, the tuning curve becomes sharper. In other words, a very small change in frequency on either side makes a large decrease in current, until curve *d* is quite sharp.

This is the method by which radio and telephone circuits are tuned sharp. Resonance is highly important in communications circuits, in order that the receiver will pick up only a certain tuned frequency, and will shut out neighboring frequencies.

PARALLEL CIRCUITS

Actually, you'll run into many more PARALLEL circuits in electrical systems than you will find SERIES circuits, since distribution and transmission of a. c. are generally handled by parallel circuits.

In solving these parallel circuits, you'll find vectors of great help, since in finding the current through several parallel loads, you find the current through each load, and then add these loads by vectors to obtain the resultant current.

A problem may help you see the solution of parallel circuits—

You have a 12-ohm resistance, a 10-ohm inductive reactance, and an 18-ohm capacitive reactance in parallel across a 110-volt, 60-cycle line, as in figure 72. Find: (*a*) Total current; (*b*) circuit power factor; and (*c*) power.

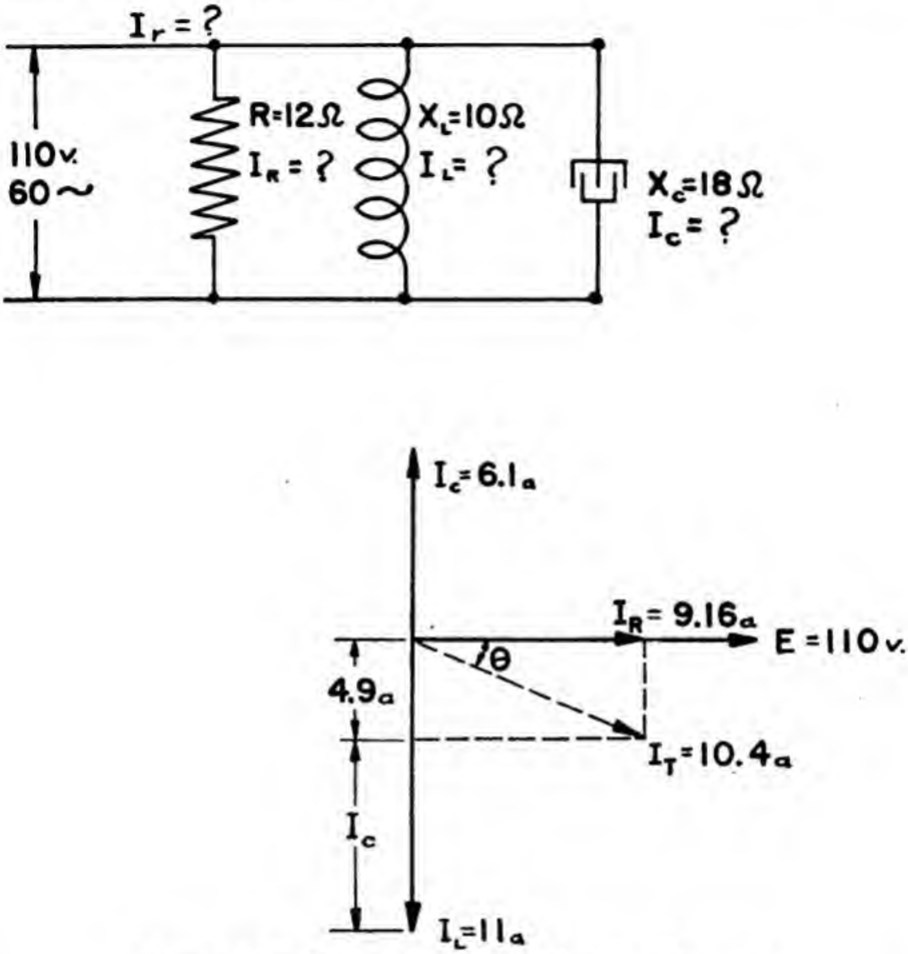


Figure 72.—Circuit diagram and vector diagram.

First, find the current through each leg of the circuit.

$$I_R = \frac{E}{R} = \frac{110}{12} = 9.16 \text{ a.}$$

$$I_L = \frac{E}{X_L} = \frac{110}{10} = 11 \text{ a.}$$

$$I_C = \frac{E}{X_C} = \frac{110}{18} = 6.1 \text{ a.}$$

Next, draw the vector diagram, shown at the bottom of figure 72. Lay off $E = 110$ v. as a horizontal vector, since the voltage is the same throughout the circuit.

Then, since current through a resistance is IN PHASE with voltage, you can lay off I_R to scale along vector E.

Now, remembering that current through an inductance LAGS voltage, lay off I_L to scale and 90° BEHIND I_R. And since current through a capacitance LEADS voltage by 90°, lay off I_C to scale 90° AHEAD of I_R.

Since I_L and I_C are in direct opposition, ADD them by vectors, and you get $I_L + (-I_C)$ or $(11 - 6.1) = 4.9$ a., LAGGING.

Then, (*a*) $I_T = \sqrt{(9.16)^2 + (4.9)^2} = \sqrt{83.9 + 24} = \sqrt{107.9}$
$= 10.4$ a. (Ans.)

And, (*b*) P. F. $= \cos\theta = \frac{I_R}{I_T} = \frac{9.16}{10.4} = 0.882$
$= 88.2$ percent. (Ans.)

So, (*c*) $P = EI_R = 110\ (9.16) = 1008$ watts. (Ans.)

RESONANCE IN A PARALLEL CIRCUIT

A parallel circuit is in resonance when the resultant current is in phase with the line voltage. In this case, inductance current and capacitance current must be equal. Since they oppose each other, they will cancel, leaving only resistance current in the circuit. Look at figure 73.

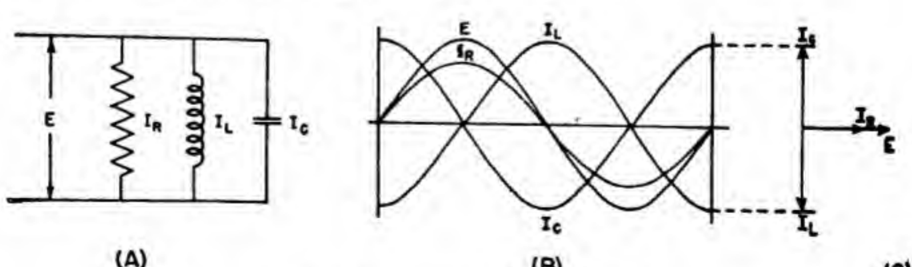


Figure 73.—Resonance in a parallel circuit.

Figure 73(A) is the circuit diagram. Figure 73(B) is the sine curve diagram and shows the relationship between voltage E, resistance current I_R, inductance current I_L, and capacitance current I_C. From figure 73(C), the vector diagram of the currents and voltage, you see that I_C leads I_L by 180°. I_C is equal to I_L and the two voltages cancel each other.

You will notice that I_T, or total current in the PARALLEL circuit, is a MINIMUM when the circuit is in resonance. But in a SERIES circuit, I_T is MAXIMUM when the circuit is in resonance. Here's why. In a PARALLEL circuit, inductance and capacitance CURRENTS are equal and opposite at the resonance point. But in a SERIES circuit, inductance and capacitance VOLTAGES are equal and opposite at the resonance point. Read this paragraph again to get the difference straight in your mind.

ACTUAL CIRCUIT CONDITIONS

Up to now, you've been assuming that the inductance and capacitance circuits you're handling are perfect—no resistance, no current losses, and with inductance and capacitance currents exactly 90° away from their voltages. Actually, though, the wire in an inductance coil must have SOME resistance, and iron-core coils have core losses equivalent to resistance. You can't design impedance coils commercially that have a phase angle better than about 87°. And even the best condensers fall a little short of 90° phase angle.

As a result of these various losses and resistances and angles short of 90°, you'll have to make slight adjustments in the actual problems you'll face in dealing with a. c. Probably a typical actual problem will show you what we mean.

HERE'S THE PROBLEM—AND SOLUTION

An impedance coil and a resistance are in series in a circuit having 110 volts of 60-cycle a. c. across the lines. The current is 6 amps. By using a voltmeter, you've found that the voltage across the resistance is 65 volts, and the voltage across the impedance coil is 85 volts. You want to know (*a*) value of the resistance coil; (*b*) circuit P. F. angle and P. F.; (*c*) impedance-coil P. F. angle and P. F.; (*d*) circuit power; (*e*) impedance-coil power; (*f*) impedance-coil resistance; and (*g*) impedance-coil reactance. Quite a lot, but easy to get.

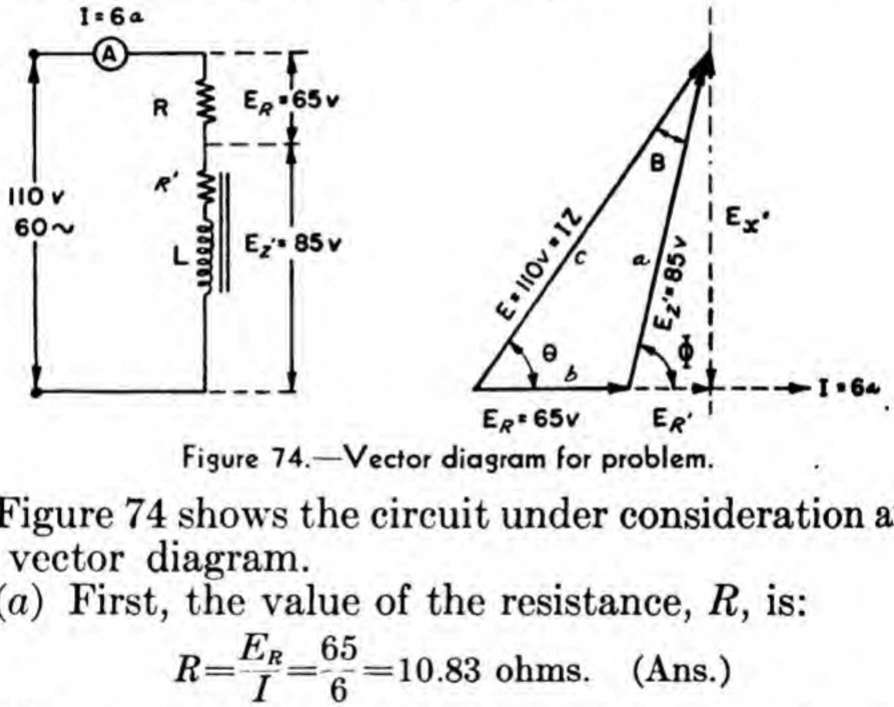


Figure 74.—Vector diagram for problem.

Figure 74 shows the circuit under consideration and its vector diagram.

(*a*) First, the value of the resistance, *R*, is:

$$R=\frac{E_R}{I}=\frac{65}{6}=10.83 \text{ ohms.} \quad \text{(Ans.)}$$

(*b*) Next, the circuit Power Factor angle, θ is found by using the Law of Cosines, as follows:

$$Cos\ \theta=\frac{b^2+c^2-a^2}{2bc}=\frac{(65)^2+(110)^2-(85)^2}{2(65\times110)}$$

$$=\frac{4{,}225+12{,}100-7{,}225}{14{,}300}$$

$$=\frac{9\text{-}100}{14{,}300}=\cdot6363$$

Therefore, $\theta=50.5°$ (approx.)
And, $P.\ F.\ =63.63\%$ } (Ans.)

(c) To find the impedance-coil Power Factor angle Φ, use the Law of Sines, as follows:

$$\sin B = \frac{b \sin \theta}{a} = \frac{65(.7716)}{85} = .5900$$

Therefore, $B = 36.2°$ (approx.)

$$\left.\begin{array}{l}\text{However, } \Phi = \theta + B = 50.5° + 36.2° = 86.7° \\ \text{And, } P.F. = \cos \Phi = \cos 86.7° = .0576 = 5.76\%\end{array}\right\} \text{(Ans.)}$$

(d) To find the circuit power, P, we use the formula: $P = EI \cos \theta$

$$= 110 \times 6 \times .6363 = 419.96 \text{ watts} \quad \text{(Ans.)}$$

(e) To find the impedance-coil power, P_z', we use the formula:

$$\left.\begin{array}{l}P_Z' = E_Z' \times I \times \cos \Phi \\ \quad = 85 \times 6 \times .0576 = 29.38 \text{ watts}\end{array}\right\} \text{(Ans.)}$$

To check this answer, consider the fact that:

$$P_R = E_R I = 65 \times 6 = 390 \quad \text{watts}$$

and, circuit power, $P = P_R + P_Z' = 390 + 29.38 = 419.38$ watts

(f) To find the impedance-coil resistance, R', we can use the formula: $P_Z' = (I^2)\ (R')$

or,

$$R' = \frac{P_Z'}{I^2} = \frac{29.38}{(6)^2} = .815 \text{ ohms} \quad \text{(Ans.)}$$

(g) To find the impedance-coil reactance, X', we use the formula:

$$\sin \Phi = \frac{E_X'}{E_Z'}$$

or, $E_X' = E_Z' \sin \Phi = 85\ (.0576) = 4.896$ volts.

Since:

$$X' = \frac{E_X'}{I} = \frac{4.896}{6} = .816 \text{ ohms.} \quad \text{(Ans.)}$$

THREE-PHASE ALTERNATORS

In the discussion of the simple a-c alternator, you used a single loop or several loops connected in series. You needed only two leads to carry the current from the generator to the load. This type of a generator is known as a SINGLE-PHASE GENERATOR, since it generates only ONE current and voltage. A generator constructed so that THREE SEPARATE WINDINGS are used is more efficient. The three windings are spaced 120° apart.

You have three coils spaced 120° apart, rotating in a steady magnetic field, as shown in figure 75. As coil *A* passes under the north pole, a voltage will be induced. If the circuit is complete, a current will flow out at point *a*. After the armature has rotated 120°, coil *B* will occupy the same position as coil *A* in the diagram. Likewise, in this position, current will flow

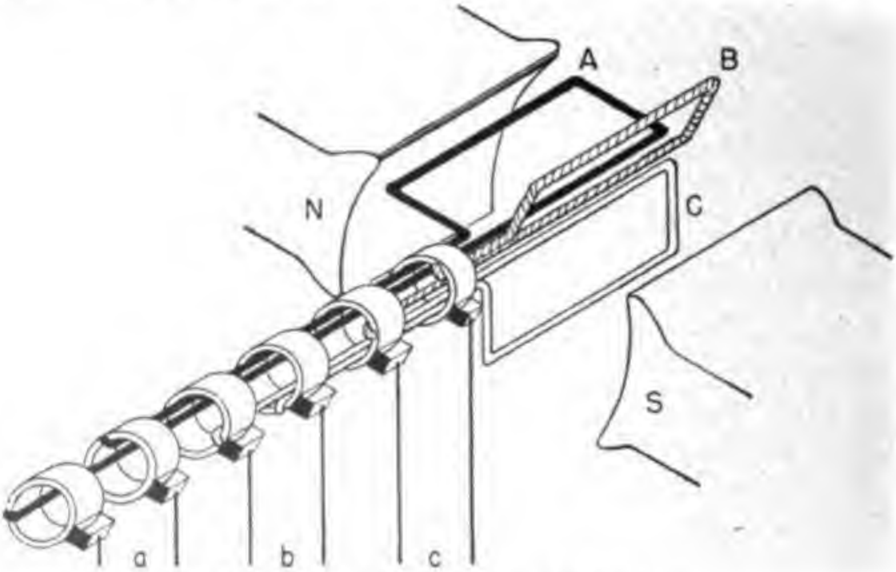


Figure 75.—Three-phase alternator.

out at *b*. The same will be true for coil *C*. By using TWO slip rings for each coil, you can lead the current to the load through six wires. The result would be about the same as if you built three separate generators into one machine.

Figure 76 shows the voltage waves from the three coils. The curve for coil *A* starts its increase 120° BEFORE coil *B*. Likewise, the curve for coil *B* starts

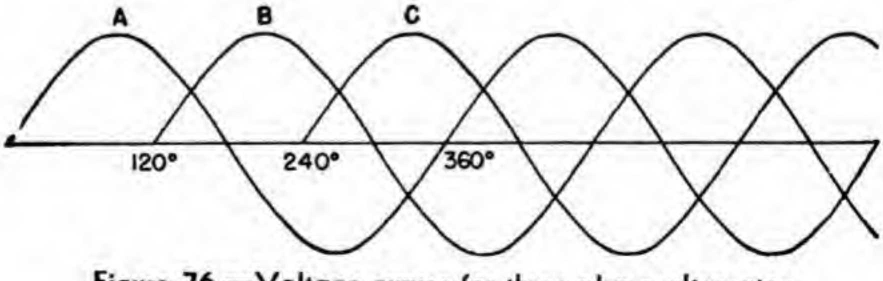


Figure 76.—Voltage curves for three-phase alternator.

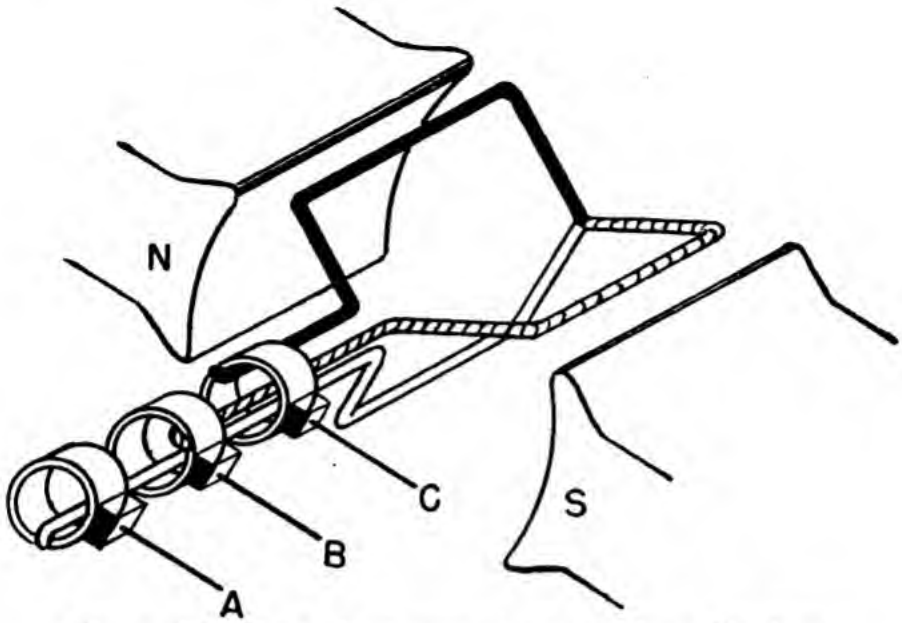


Figure 77.—Three-phase generator using three slip-rings.

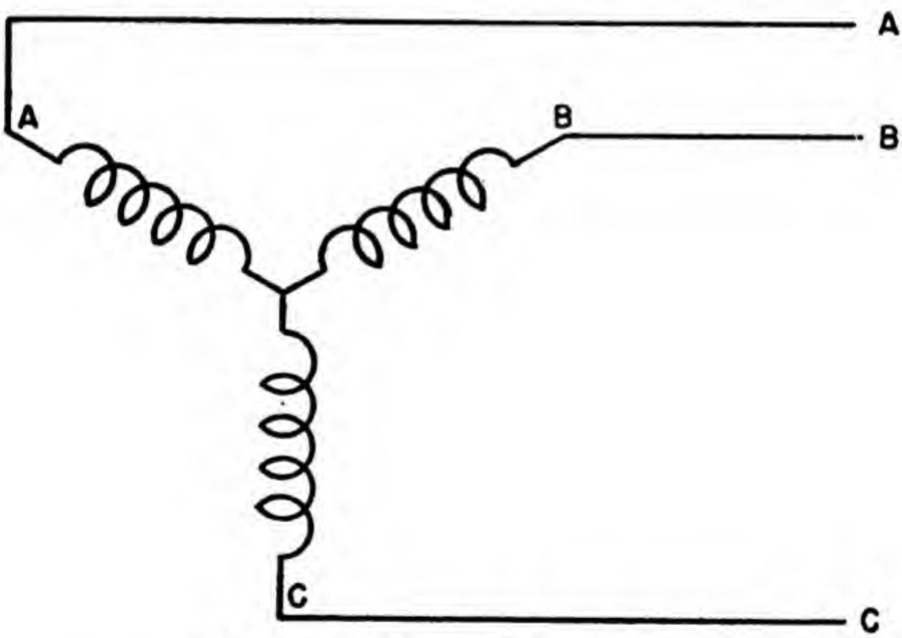


Figure 78.—Schematic of figure 77.

its increase 120° before coil *C*. The result is, therefore, THREE SEPARATE VOLTAGES, 120° apart in phase-relation to each other.

Now connect the coils as shown in figure 77. You can do away with three wires and yet maintain your THREE-PHASE system. This is the way three-

phase generators are usually connected. Schematic diagrams are shown in figure 78. This type of connection is known as STAR, OR WYE (Y) CONNECTION. In many three-phase generators, the WINDINGS are placed on the frame or YOKE of the generator, and the FIELD is the ROTATING part. Thus, a positive con-

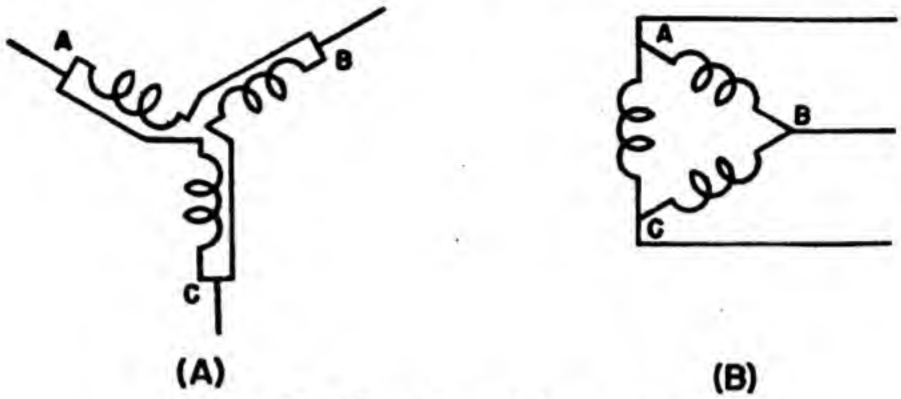


Figure 79.—Three-phase delta connection.

nection can be made to the generator windings, and only two slip rings are needed to carry the current to the field poles.

Another type of connection you will use in three-phase systems is the Δ, or DELTA, connection shown in figure 79. The same phase-difference exists in the delta connection as in the Y connection. Notice that

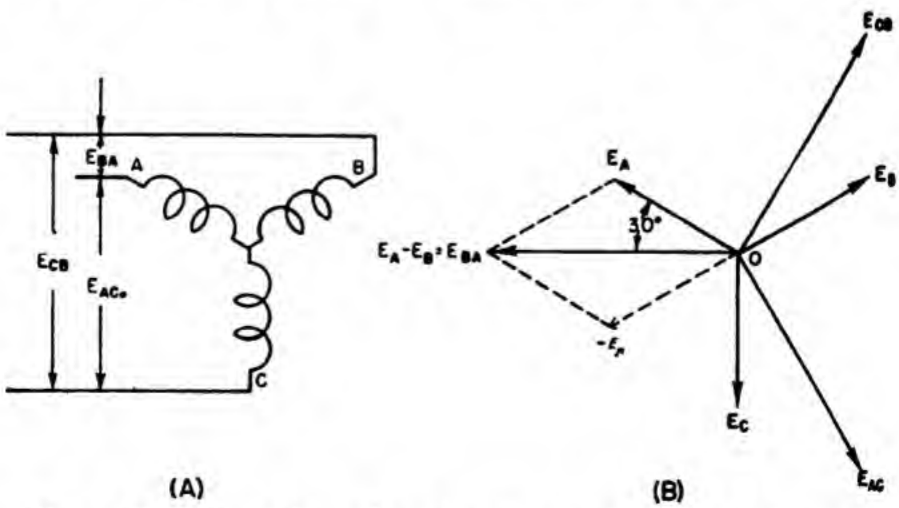


Figure 80.—Three-phase "wye" connection and vector diagram.

the delta is similar to it in that the coils generate voltages in the same direction and magnitude.

In order to better understand the three-phase system, study its vector diagram. Figure 80 shows the schematic and vector diagram of a balanced Y-connected system. The individual phase voltages E_A, E_B, and E_C, act from the point O out in each direction. On the other half of the cycle they would act in the opposite direction, but for the purpose of discussion we shall deal with INSTANTANEOUS values. The LINE VOLTAGE, E_{BA}, is the vector DIFFERENCE between phase voltages E_A and E_B.

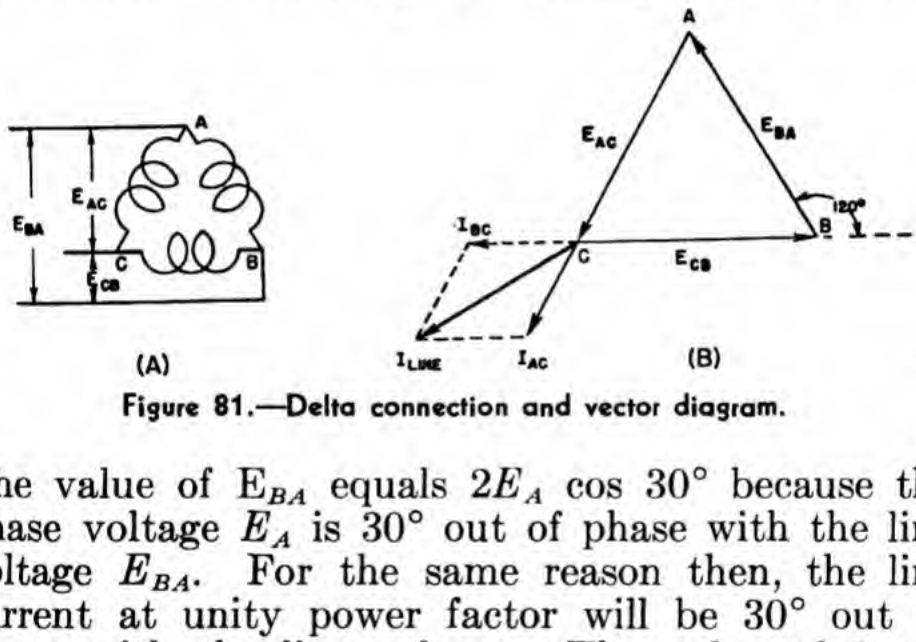


Figure 81.—Delta connection and vector diagram.

The value of E_{BA} equals $2E_A \cos 30°$ because the phase voltage E_A is 30° out of phase with the line voltage E_{BA}. For the same reason then, the line current at unity power factor will be 30° out of phase with the line voltage. The value of 2 cos $30° = \sqrt{3}$. Therefore, $E_{BA} = \sqrt{3}\, E_A$.

You see the vector diagram for a DELTA connection in figure 81. The voltage developed in each of the coils is shown by corresponding vectors. By extending line E_{CB} you see that E_{CB} and E_{BA} are 120° out of phase. This is also true for the other voltages. However, the LINE voltage in this case is equal to the COIL voltage. Such was not true of the Y-connected system.

Next, consider the current flowing into the line at C. If the current produced by E_{AC} and the current

produced by E_{CB} flow into the line, the current from E_{CB} must have a direction OPPOSITE to E_{CB}, as shown by I_{BC}. When this current is combined with I_{AC}, the

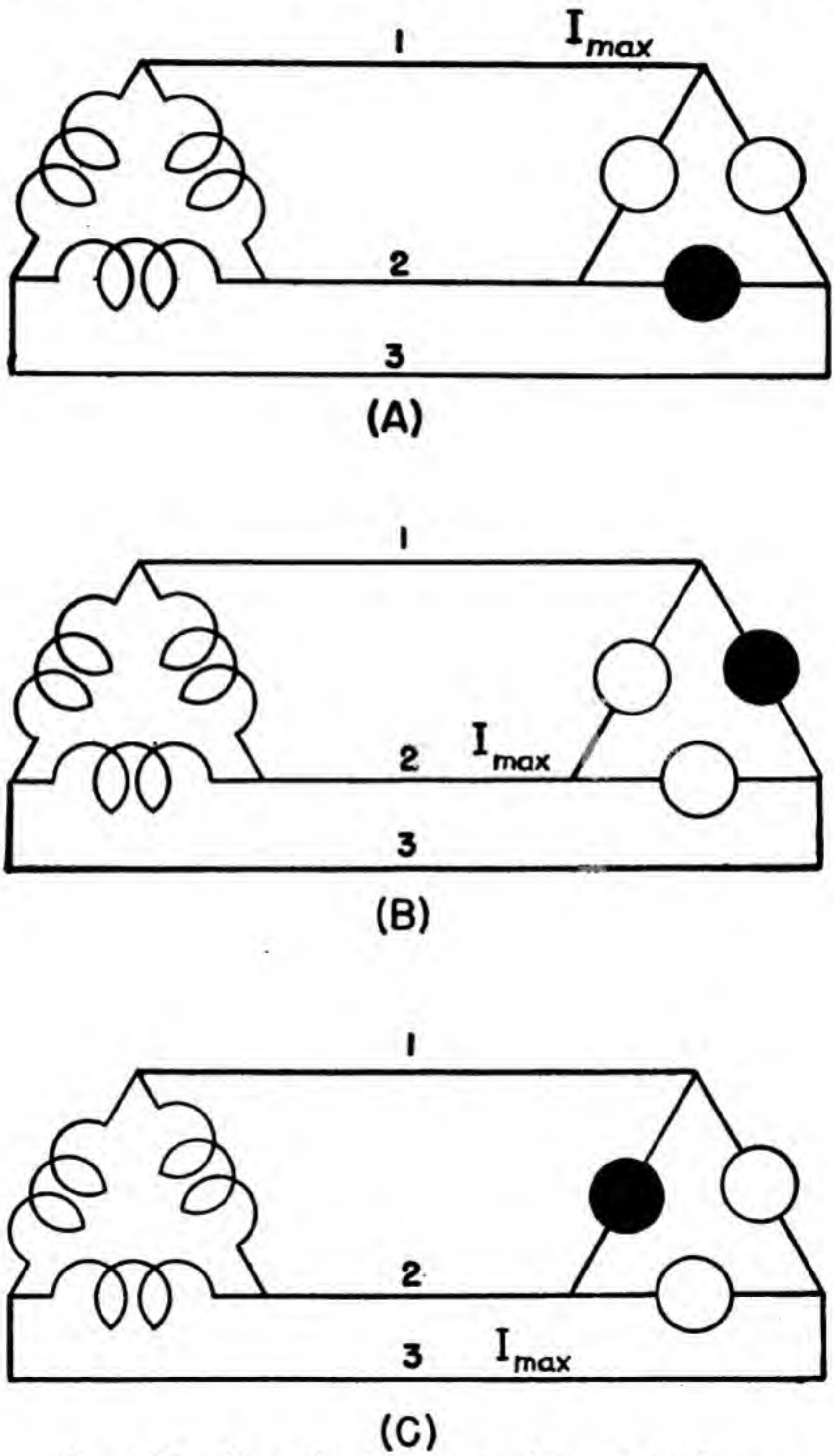


Figure 82.—Three-phase sequence of current maximum.

resultant line current is I_L. From this diagram it can be seen that this CURRENT, L_L, is 30° OUT OF PHASE with the PHASE VOLTAGE, E_{AC}. Therefore, the LINE CURRENT in a DELTA-connected system is equal to $\sqrt{3}$ times the PHASE current. Or—

$$I_L = \sqrt{3}\ I_{phase}$$

The three-phase cycle is shown in figure 82. A DELTA-connected system is connected to a delta of lamps. In A, the current in line 1 is a maximum and flows out through two lamps and returns through lines 2 and 3. One lamp does not burn because no voltage is applied to it. In B, the current is maximum through line 2 and returns through lines 1 and 3. This time the lamp between 1 and 3 is out. In C, the maximum current flows in line 3 and the lamp between line 1 and 2 is out. Of course, as with all incandescent lamps, the filaments do not have time to cool and therefore do not actually go out while no current flows through them.

POWER IN A THREE-PHASE CIRCUIT

The CURRENT in phase OA is in phase with the VOLTAGE OA if the system is at UNITY power factor. See figure 83. This is also true for each of the other

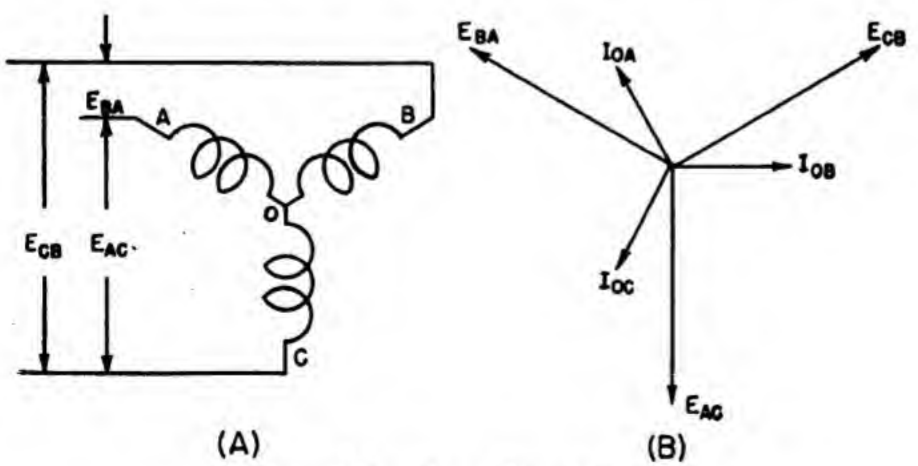


Figure 83.—Three-phase power.

phases. Therefore, the TOTAL POWER is given by the formula—

$$P=3E_{phase}I_{phase}$$

where

$$I_{phase}=I_{line}$$

However, the LINE VOLTAGE is equal to $\sqrt{3}E_{phase}$ Thus, if you substitute E_{line} for E_{phase}, the formula becomes—

$$P=\frac{3E_{line}I_{phase}}{\sqrt{3}}=\sqrt{3}E_{line}I_{line}.$$

If the power factor is NOT UNITY, then the phase current will lag or lead the phase voltage by an angle θ. Therefore, the TOTAL POWER formula in the line will become—

$$P=3E_{phase}I_{phase}\cos\theta_{phase}$$

and

$$P=\sqrt{3}E_{line}I_{line}\cos\theta_{line}.$$

This is the general power formula for three-phase circuits. In the case of a delta-connected system, the phase voltage and line voltage are the same, but the line current is $\sqrt{3}$ times the phase current. Thus, the same formula holds true.

TRANSFORMER CONNECTIONS FOR THREE-PHASE CIRCUITS

In most transformer connections for THREE-PHASE circuits, SINGLE-PHASE TRANSFORMERS are used. The PRIMARIES are connected in either Y or DELTA, and the SECONDARIES are connected in a similar manner.

Figure 84 shows the transformer connections for Y-TO-Y and DELTA-TO-DELTA systems. In this type of connection, the VOLTAGE ratio between primary and secondary is determined by the TURNS ratio.

That is, if 100 volts between lines on the primary is applied and the turns ratio is 2 to 1, the voltage between lines of the secondary wire will be 50 volts.

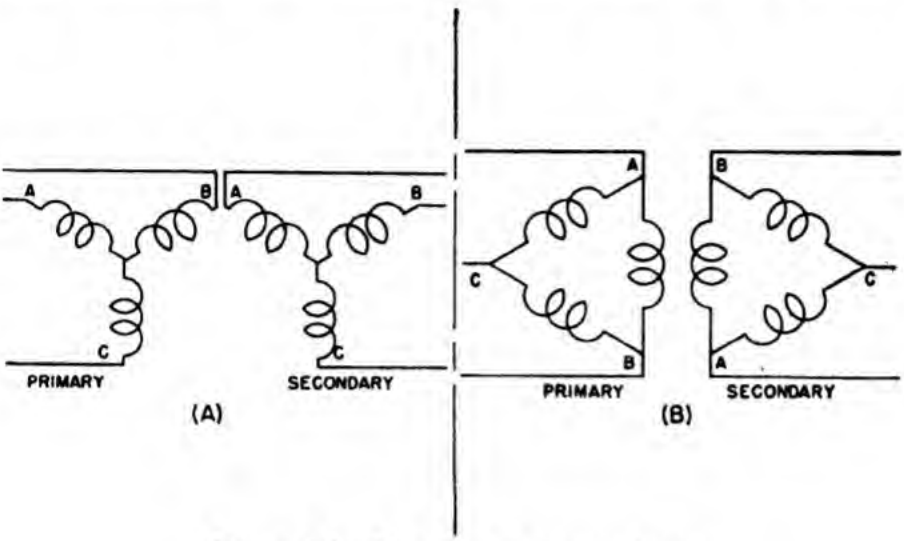


Figure 84.—Transformer connections.

Figure 85 illustrates Y-TO-DELTA and DELTA-TO-Y connections for THREE-PHASE transformers. In this case, the voltage on the secondary is affected by the method of connection, as well as by the turns-ratio. Suppose that a 1-to-1 ratio exists in each case. If

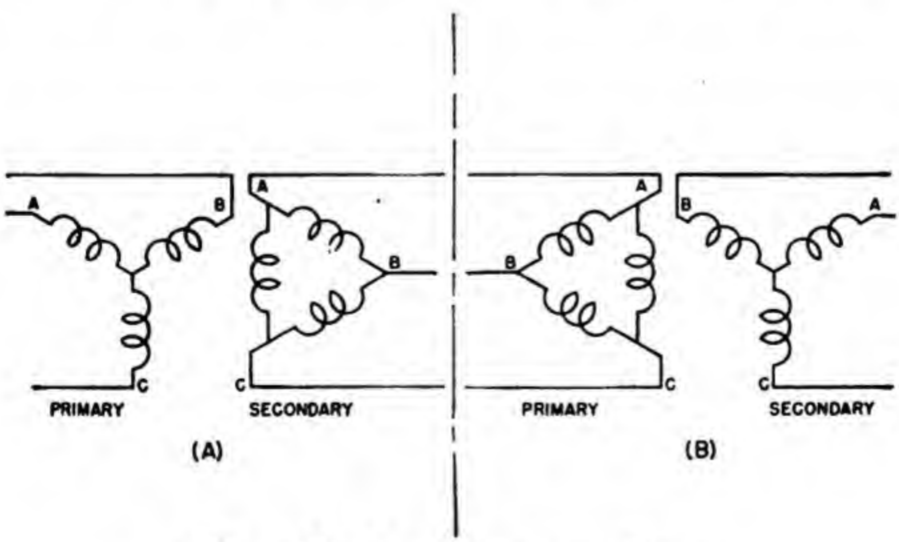


Figure 85.—Transformer connections.

you have a voltage of 173 volts between lines of the primaries in (A), then the line voltage of the secondary will be the same as phase voltage (or 100 volts.)

If the 173 volts were applied to the primaries of the delta connection in (B), the secondary line voltage would be 300 volts.

Other special type connections can be used, but they are beyond the range of this book.

CHAPTER 6

D-C ARMATURE WINDING

TORQUE AND EMF

The ARMATURES of the d-c generator and motor are the most important parts of the machines. In the generator, the armature produces the generated EMF. In a motor, the armature is used to make the impressed emf produce TORQUE to turn the rotor.

You need to learn armature construction and methods of winding armatures for one important reason: So you will be able to repair an armature having a defective winding.

There are two general types of windings. These are the GRAMME-RING and the DRUM-TYPE windings. (The gramme-ring type is obsolete, and will not be discussed here.) The DRUM-TYPE WINDING is separated into TWO classes—the LAP-WOUND ARMATURE, and the WAVE-WOUND ARMATURE.

DRUM WINDINGS

The conductors of the DRUM WINDING all lie upon the surface of the rotor and are connected to one another by front and back connections. ALL the coils on the drum cut across the magnetic field and are active in generating emf, or torque.

In figure 86 you see a drum-wound armature with two coils in place. The two sides of each coil are separated from each other by the distance between two adjacent poles of the stationary frame of the

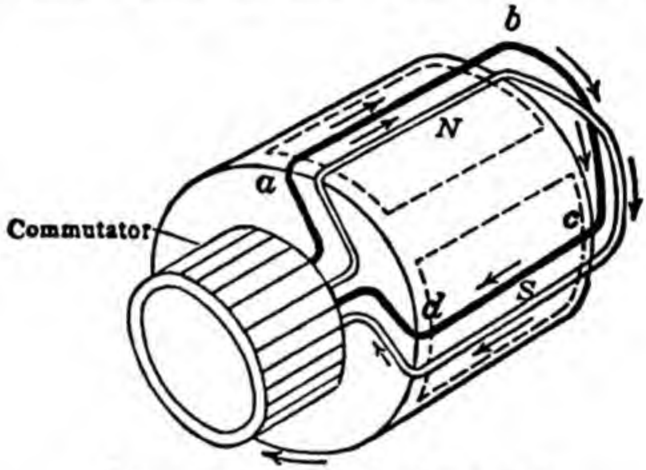


Figure 86.—Drum-wound armature.

motor or generator. This distance is called POLE PITCH. If one side of a coil is under a NORTH pole, the other side will be under an adjacent SOUTH pole. Since both sides of the coil are moving in the same direction, but are under unlike poles, the emf's induced in the two sides of the coil will be in opposite directions. You connect these conductors together so that the emf's induced in each side of the coil will ADD to each other.

In the drum-wound armature, the coils are embedded in slots. These slots are lined with insulation and the conductors are held firmly in place by fiber or other nonconducting wedges.

Two types of drum windings are commonly used—the LAP-WOUND and the WAVE-WOUND ARMATURES.

The lap-wound armature is the simplest, and will be discussed first.

The lap- and wave-wound armatures can be wound either as a single, double, or triple winding. In the single or SIMPLEX winding, there is only one winding on the core. There are TWO windings for the DUPLEX and THREE windings for the TRIPLEX. If you use two or three windings, you double or triple the cur-

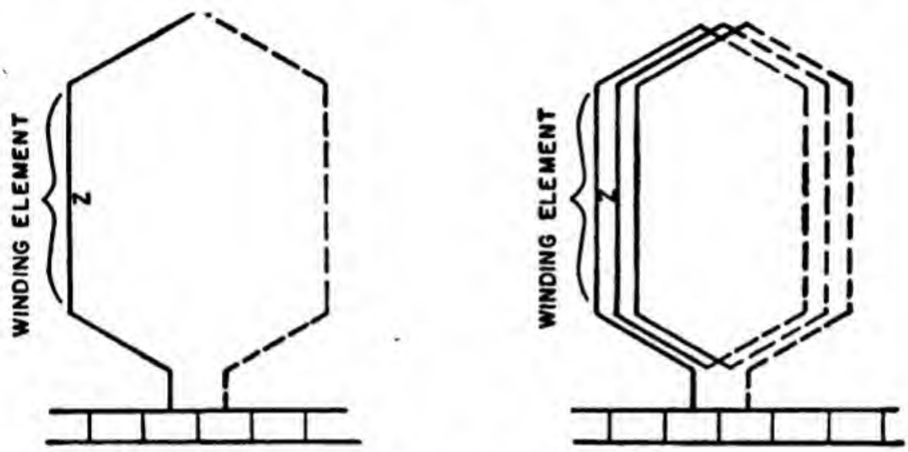


Figure 87.—Winding elements.

rent output of the machine. In other words, the current output of a triplex winding is three times that of a simplex. However, the TERMINAL VOLTAGE of the triplex generator would be only one-third that of the simplex winding.

In the study and design of windings, you call the group of wires which constitutes the side of a single coil a WINDING ELEMENT. Look at figure 87. This winding element may be made up of several conductors, but in a wiring diagram they will always appear as a single conductor. There are always TWICE as many WINDING ELEMENTS as there are COILS.

The number of elements that the coil advances on the back of the armature is the BACK PITCH of the

winding, and is symbolized by y_B. The number of elements spanned on the commutator end of the armature is called the FRONT PITCH, and is symbolized by y. In a lap-wound armature, the front pitch may be greater or less than the back pitch BUT NOT EQUAL TO IT.

For convenience and clarification, give the elements lying in the tops of the slots odd numbers and those in the bottoms of the slots even numbers. If one side of the coil lies in the bottom of a slot, the other side must lie in the top of some other slot.

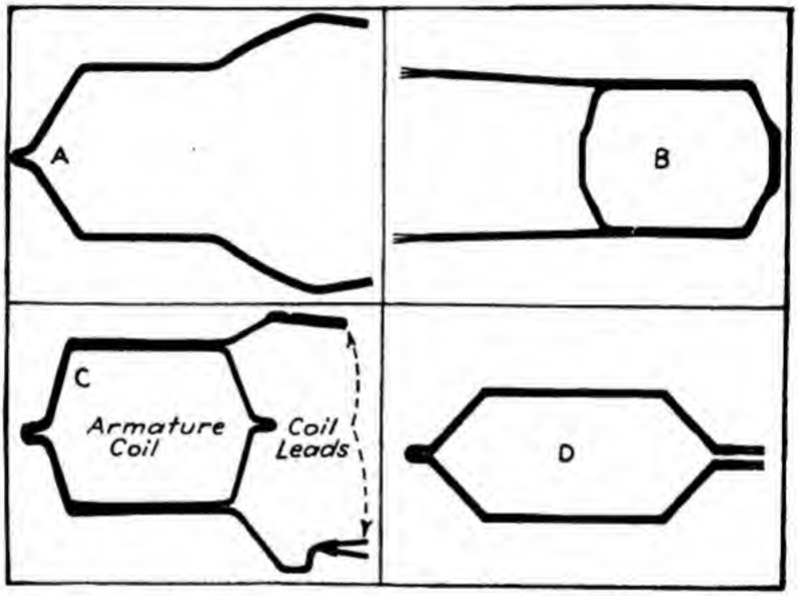


Figure 88.—Form-wound coils.

A winding may either be RETROGRESSIVE OR PROGRESSIVE. If the front pitch is GREATER than the back pitch the winding is said to be RETROGRESSIVE. If the front pitch is LESS than the back pitch the winding is said to be PROGRESSIVE. If you look at the armature from the commutator end, a RETROGRESSIVE WINDING advances in a COUNTERCLOCKWISE direction.

As you know, the span of a coil should be equal to the pole pitch. To get the AVERAGE span y of a

coil, divide the number of winding elements, Z by the number of poles, p. Thus—

$$y=\frac{Z}{p}$$

If y comes out EVEN, you cannot use it for either the back or front pitch, but if y is ODD, you can use it as the back OR front pitch. It is generally used as the BACK pitch. As a check for a well-spaced winding, y should be the sum of the back and front pitch divided by 2, or—

$$y=\frac{y_b+y_f}{2}$$

LAP WINDINGS

Direct-current armatures are usually wound with form-made coils. Different types of formed coils are shown in figure 88. These coils are wound and formed by machine. The ends are left bare so that they may be soldered later to the COMMUTATOR BARS. The span of the coil, or COIL PITCH, should be equal, or about equal to the POLE PITCH.

If the coil span is made less than the pole pitch the result is slightly better commutation—as well as a saving in copper in the end connections. Such a winding is called a FRACTIONAL-PITCH WINDING. With direct-current machines, the pitch may be as low as nine-tenths of full pitch. If the pitch is too small, you get too great a reduction in the induced emf.

Usually you put two coil sides (which may be made up of several coils) in one slot. One coil side lies at the top and the other at the bottom of the slot. In other words, if one side of a coil is in the BOTTOM of a slot, its opposite side lies in the TOP of some OTHER slot. This allows you to make the end connections easily since the coil ends can be bent around one another in a systematic manner, passing from the

bottom layer to the top layer by means of a peculiar twist in the ends of the coil.

In the simple lap type of drum winding, you make the coil connection from one segment of the commutator, through the two sides of the coil, and thence back to the next adjacent segment. From this segment, a similar connection is made to the next coil, and so on around.

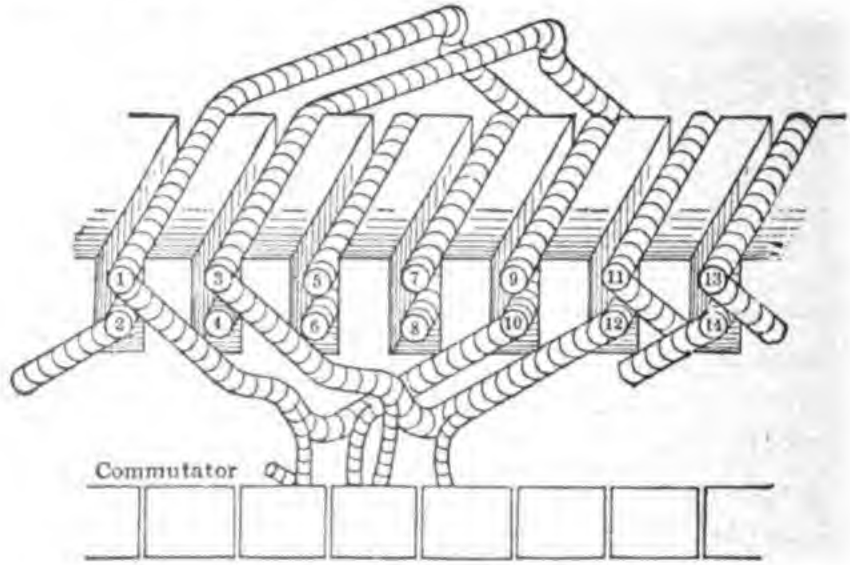


Figure 89.—Simplex lap winding.

In figure 89, you see a simplex lap winding having a back pitch of 9 and a front pitch of 7. It follows from this that the front pitch differs from the back pitch by 2. By formula—

$$y_b = y_f \pm 2$$

The plus-or-minus sign ($\pm$) indicates a progressive or retrogressive winding.

You must have one commutator segment for every COIL or every pair of elements. Therefore, the number of segments comprising the commutator will be equal to the number of coils, N, or to the number of winding elements, Z, divided by 2. The number of commutator segments is symbolized by N_c.

$$N_c = N = \frac{Z}{2}$$

Look at figure 89 again, and you will see that the winding advances one commutator segment for each complete turn. In this winding, the commutator pitch y_C, is equal to 1. Here are three fundamental conditions to be fulfilled by a LAP winding:

THE PITCH MUST BE SUCH THAT THE OPPOSITE SIDES OF A COIL LIE UNDER ADJACENT UNLIKE POLES.

THE WINDING MUST INCLUDE EACH ELEMENT ONCE AND ONLY ONCE.

THE WINDING MUST CLOSE ON ITSELF. (That is, you must have two elements in each slot, only two, and no empty slots).

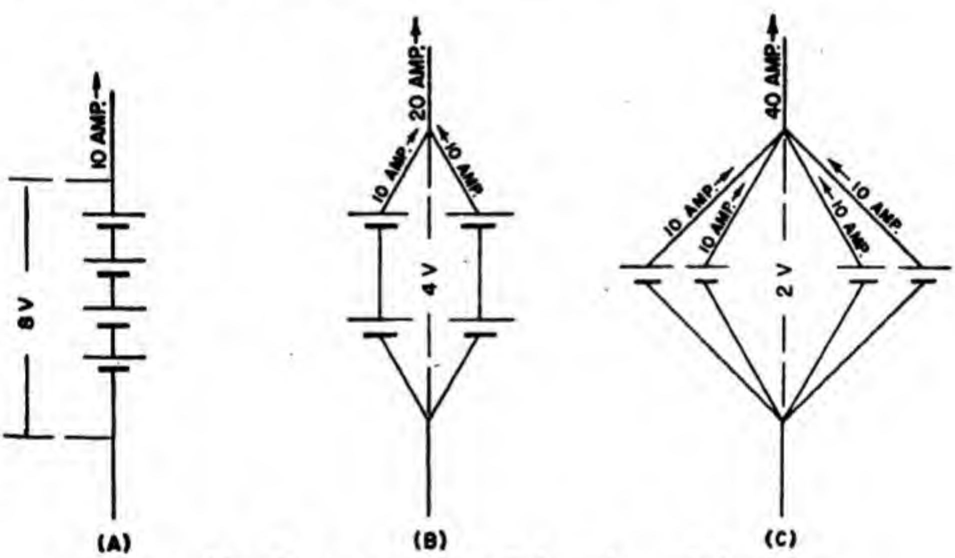


Figure 90.—Series, series-parallel, and parallel circuits.

PATHS THROUGH ARMATURE

Each armature conductor supplies emf, and in the ordinary machines these emf's are all equal. You connect the conductors in different combinations so that there will be two, four, or more paths through the armature, depending on the rating of the machine.

Now use this battery illustration to explain armature conductors. In figure 90, four 2-volt batteries, with a current rating of 10 amperes each, are con-

nected in SERIES, SERIES-PARALLEL, and PARALLEL. In figure 90 (*A*) the four cells are connected in SERIES, giving a voltage of 8 volts and supplying a current of 10 amperes to the load. In figure 90 (*B*), the batteries are connected in SERIES-PARALLEL. Now the voltage will be 4 volts but there are two paths for the current to flow. The total current now being supplied to the load is 20 amperes. Each side of the series-parallel branch applies 10 amperes.

In figure 90 (*C*), the four batteries are connected in PARALLEL. Now the voltage is 2 volts but there are four paths for the current to flow. In this case the total current will be 40 amperes. But in each case there is a total power of 80 watts supplied to the external circuit. The power rating is independent of the manner in which the connections are made.

Remember that IN ALL SIMPLEX LAP WINDINGS THERE ARE AS MANY PATHS THROUGH THE ARMATURE AS THERE ARE POLES.

DESIGN A LAP WINDING

(This design does not include the selection of the coils as to the size of wire and the number of turns used in each. The size of wire and number of turns used to make up a coil depends upon the rated power of the machine.)

Design an armature for a 4-pole generator. There are 20 slots in the rotor and the winding is to be a 2-layer, simplex lap-winding, with two coils per slot. The winding is to be progressive. You must determine (*1*) the number of winding elements, (*2*) a suitable back pitch, (*3*) a suitable front pitch, (*4*) the number of commutator segments. (*5*) Make a winding chart. (*6*) Make a sketch of the winding.

The step-by-step procedure outlined below is standard for the design of any simplex lap-wound armature.

GIVEN—

(*1*) 4-pole generator.
(*2*) 20-slot armature core.
(*3*) Progressive lap winding.

TO DETERMINE—

(*1*) Number of winding elements (Z).
(*2*) Suitable back pitch (y_b).
(*3*) Suitable front pitch (y_f).
(*4*) Number of commutator segments (N_c).
(*5*) Make winding table.
(*6*) Make sketches of winding.

PROCEDURE—

1. Find number of elements—

$Z = 2 \times \text{number of slots} = 2 \times 20 = 40$ elements (Ans.)

2. Find back pitch—

$y = \frac{Z}{p} = \frac{40}{4} = 10$, average pitch

But since neither the back pitch nor the front pitch can be an EVEN number, you must ASSUME a back pitch (y_b). In this case choose a back pitch of 11.

$y_b = 11$ (Ans.)

3. Find front pitch—

$y_f = y_b \pm 2$

In this case of a PROGRESSIVE WINDING, the FRONT pitch (y_f) must be smaller than the BACK pitch (y_b). The formula will then become—

$$y_f = y_b - 2 = 11 - 2 = 9 \quad \text{(Ans.)}$$

4. Find number of commutator segments—

$$N_c = \frac{Z}{2} = \frac{40}{2} = 20 \quad \text{(Ans.)}$$

5. Develop a winding table—

Start with Element 1. Add y_b, or the back pitch, to it. The opposite conductor from Element 1 will be $1+y_b$, or $1+11$, away in slot 12. Then subtract y_f, or 9, from slot 12, and the left-hand conductor of Coil 2 will lie in Slot 3. And so on. Here's the sequence of the winding—

1–12–3–14–5–16–7–18–9–20–11–22–13–24–15–26–17–28–19–30–21–32–23–34–25–36–27–38–29–40–31–2–33–4–35–6–37–8–39–10–1.

6. Draw the wiring diagram—(See figures 91 and 92).

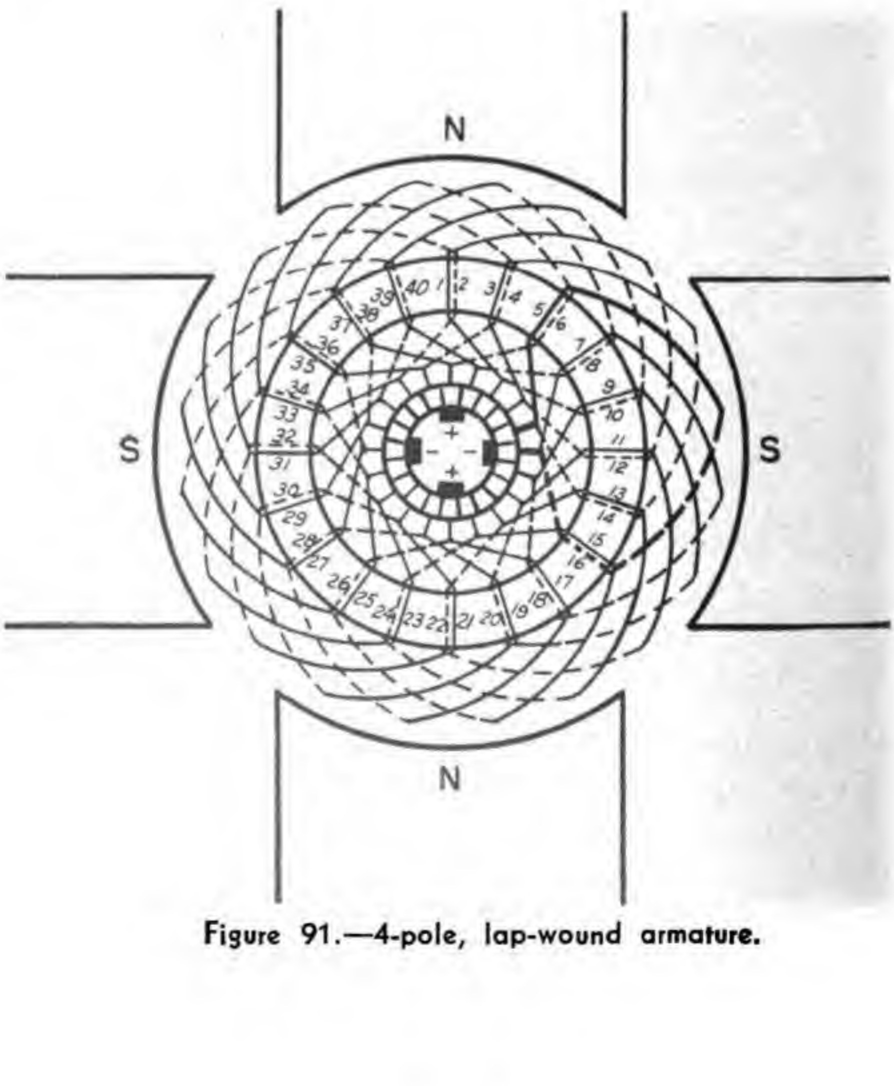


Figure 91.—4-pole, lap-wound armature.

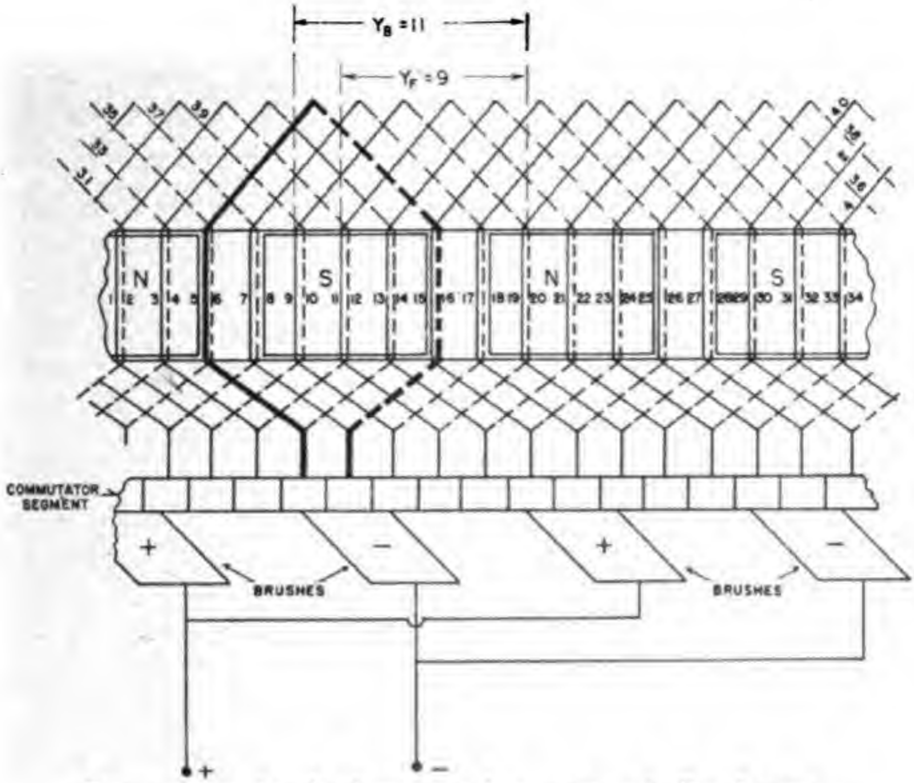


Figure 92.—4-pole, lap-wound armature winding layout.

WAVE WINDING

In the lap-wound armature, in figures 91 and 92, you connected a coil side under one pole directly to a coil side occupying a corresponding position under the next pole. Then you connected this second coil side back to a coil side under the original pole, but in a different slot. It would not make any difference in the direction and magnitude of the induced emf in the winding if the connection, instead of returning to the original pole, advanced to the next pole.

In figure 93, you see the difference between lap and wave-wound armatures. In figure 93 (*A*) you have a LAP-wound armature similar to the one used in the preceding problem and shown in figures 91 and 92. In figure 93 (*B*) you have a WAVE-WOUND ARMATURE. The windings pass all the north and south poles

before they return to the original pole. The winding, after passing once around the armature reaches conductor A' B' lying under the same pole as the initial conductor AB. When a winding advances from pole to pole in such a manner it is a WAVE winding. The front and back pitch, just as in the lap-wound armature, are used to denote the span of the coil connection on the back and front of the armature. However,

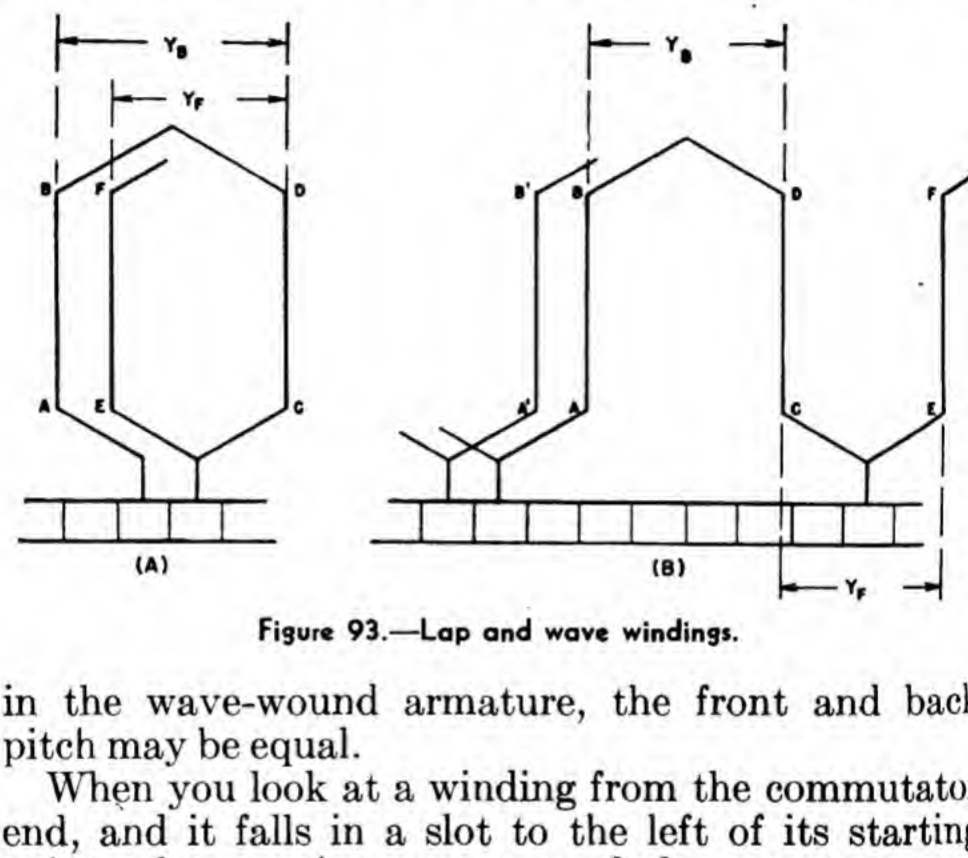


Figure 93.—Lap and wave windings.

in the wave-wound armature, the front and back pitch may be equal.

When you look at a winding from the commutator end, and it falls in a slot to the left of its starting point, after passing once around the armature, you say it is a RETROGRESSIVE winding. If a winding falls in a slot to the right of its starting point after passing once around the armature, you call it a PROGRESSIVE winding.

The wave winding is more restricted in its relation to the number of slots and coils than the lap winding, for the following reason. In a simplex wave winding, after having passed once around the arma-

ture, the winding must fall two elements either to the right or left of the element at which it started.

In the lap-wound armature, you discovered the average pitch was found by dividing the number of winding elements, Z, by the number of poles, p. If you used this formula for WAVE windings, the winding would close after passing once around the armature. You'd cause a short circuit. A WAVE WINDING MUST NOT CLOSE ON ITSELF UNTIL EVERY SLOT IS FILLED. Therefore, after passing around the armature once, the average pitch CANNOT be—

$$y=\frac{Z}{p}$$

but MUST BE—

$$y=\frac{Z\pm 2}{p}$$

The plus-or-minus sign indicates a PROGRESSIVE winding or a RETROGRESSIVE winding.

In the lap-wound armature, the number of commutator segments was equal to the number of coils, or the number of winding elements, Z, divided by 2.

Then the number of commutator segments would be—

$$N_c=\frac{Z}{2}$$

And so, the number of winding elements would be—

$$Z=2N_c$$

The pairs of poles of a machine would be the number of poles divided by 2, or—

$$p_1=\frac{p}{2} \text{ and } P=2_{p1}$$

where p_1=pairs of poles

You remember the formula for average pitch—

$$y=\frac{Z\pm 2}{p}$$

Substituting in the above equations for Z and p, the average pitch, y, becomes—

$$y = \frac{2N_c \pm 2}{2p_1}$$

or

$$N_c = p_1 y \pm 1$$

If p_1 and y are odd, the product of the two will be odd. Adding or subtracting ONE will make N_c even. Therefore, with a wave winding having an odd number for an average pitch and having 6, 10, or 14 poles the number of commutator segments and the number of coils, N_c, must be even.

But if the machine had 4, 8, or 12 poles, p_1 would be even and the product p_1y would be even. In this case, N_c would be odd.

The commutator pitch of a wave-wound armature is quite different from that used in lap-winding. The commutator pitch cannot be equal to the total number of segments divided by the pairs of poles. If this were the case, the winding would close on itself after one passage around the armature. For example, a 4-pole machine having 41 segments has a pitch of 10. The calculated pitch is 10¼. The difference in these quantities, or ¼, represents the CREEPAGE of the wave winding. This creepage is necessary in order that the winding shall not close on itself after one passage around the armature.

In a SIMPLEX WAVE WINDING, regardless of the number of poles, there are always two paths. The number of paths through a wave-wound armature depends only on the degree of multiplicity of the winding, and not on the number of poles. A simplex wave winding has two paths, a duplex winding has four paths, etc.

For comparison of lap and wave-wound armatures, look at a six-pole machine. This table gives the value of current and emf when the winding is changed.

The total number of armature conductors in all cases remains constant.

	Paths	Volts	Amperes	Kilowatts
Simplex lap	**6**	**100**	**60**	**6**
Duplex lap	**12**	**50**	**120**	**6**
Triplex lap	**18**	**33.3**	**180**	**6**
Simplex wave	**2**	**300**	**20**	**6**
Duplex wave	**4**	**150**	**40**	**6**
Triplex wave	**6**	**100**	**60**	**6**

From the table you can see that a multiple winding has a greater current output than a simplex winding, but the terminal voltage of the machine is less. Also, a wave-wound armature has a greater terminal voltage than a lap-wound armature of the same type.

NOW DESIGN A WAVE WINDING

Design the armature for a four-pole generator. There are 39 slots in the rotor and the winding desired is a two-layer, simplex wave winding, with two coils per slot. The winding is to be progressive. You are:

GIVEN—

(*1*) 4-pole generator.
(*2*) 39-slot armature core.
(*3*) Progressive wave winding.

TO DETERMINE—

(*1*) The number of winding elements.
(*2*) The average pitch.
(*3*) Back and front pitch.
(*4*) The number of commutator segments.
(*5*) Make a winding chart.
(*6*) Make a sketch of the winding.

PROCEDURE—

1. Find the number of winding elements—
$Z = N \times 2 = 39 \times 2 = 78$ (Ans.)

2. Find the average pitch—
$y = \frac{Z+2}{p} = \frac{78+2}{4} = \frac{80}{4} = 20$ (Ans.)

3. Find the back and front pitch—Since the back and front pitch of a wave winding may or may not be equal, the back and front pitch are assumed as follows—

$y_b = 21$ (Ans.)
$y_f = 19$ (Ans.)

4. Find the number of commutator segments—
$p_1 = \frac{P}{2} = \frac{4}{2} = 2$ pairs of poles
$N_c = p_1 y - 1 = (2 \times 20) - 1 = 39$ (Ans.)

5. Make the winding chart—
1–22–41–62–3–24–43–64–5–26–45–66–7–28–47–68–9–30–49–70–11–32–51–72–13–34–53–74–15–36–55–76–17–38–57–78–19–40–59–2–21–42–61–4–23–44–63–86–25–46–65–8–27–48–67–10–29–50–69–12–31–52–71–14–33–54–73–16–35–56–75–18–37–58–77–20–39–60–*1*.

6. See figure 94.

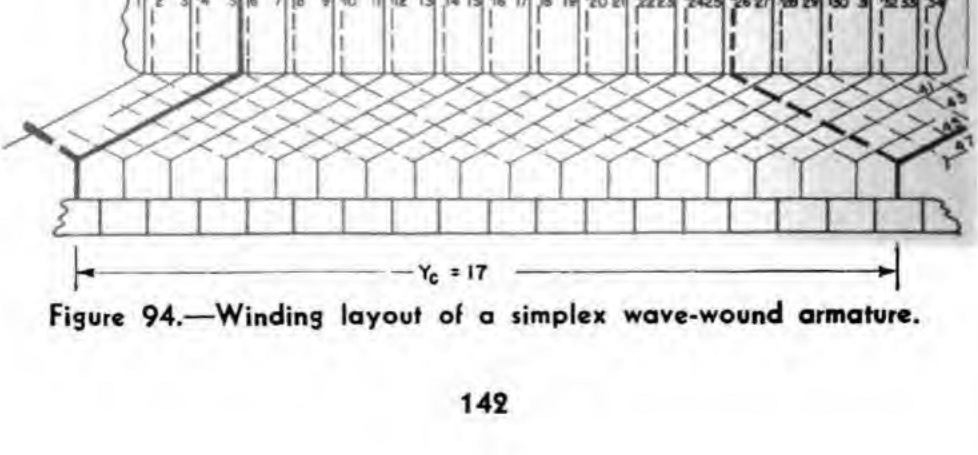
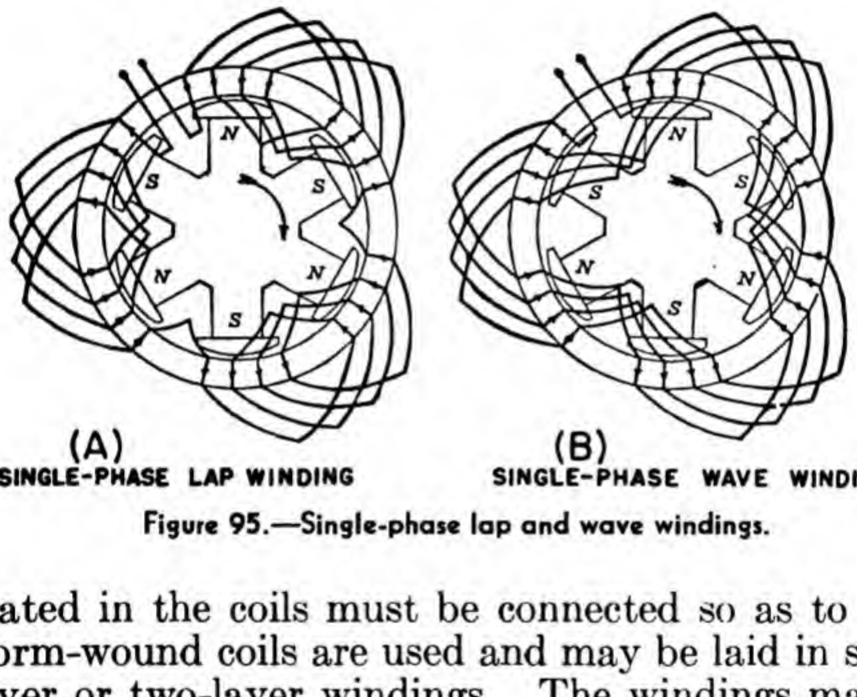


Figure 94.—Winding layout of a simplex wave-wound armature.

A-C ARMATURE WINDING

The d-c armature can be used for an alternating current machine provided properly-connected slip rings are used. You have noted, however, that the direct-current windings we've discussed were all closed-circuit windings. Open-circuit windings work much better for alternating-current machinery.

The same general principles apply to a-c windings as to d-c windings. The two sides of the coil must span approximately a pole pitch. The emf's gen-



(A) SINGLE-PHASE LAP WINDING (B) SINGLE-PHASE WAVE WINDING

Figure 95.—Single-phase lap and wave windings.

erated in the coils must be connected so as to ADD. Form-wound coils are used and may be laid in single layer or two-layer windings. The windings may be lap-wound or wave-wound.

In the d-c machine, the wave winding gives a HIGHER voltage than the lap winding, if the number of series-connected conductors and other conditions remain the same. In the a-c machine, the wave and lap-windings give the SAME voltage if the number of conductors and other conditions remain the same.

In figure 95 a lap-wound and a wave-wound alternator are shown. You see that each winding has

the same number of series-connected conductors between terminals.

When you connect all the coils in series so that there is but one set of coils terminating in two free ends, you have a SINGLE-PHASE winding. POLYPHASE windings consist merely of two or more single-phase windings symmetrically spaced on the armature.

While a-c windings are generally quite similar to d-c windings, they are usually much simpler. Much of the complexity of the d-c windings previously described resulted from having to make proper connections to the same commutator bars.

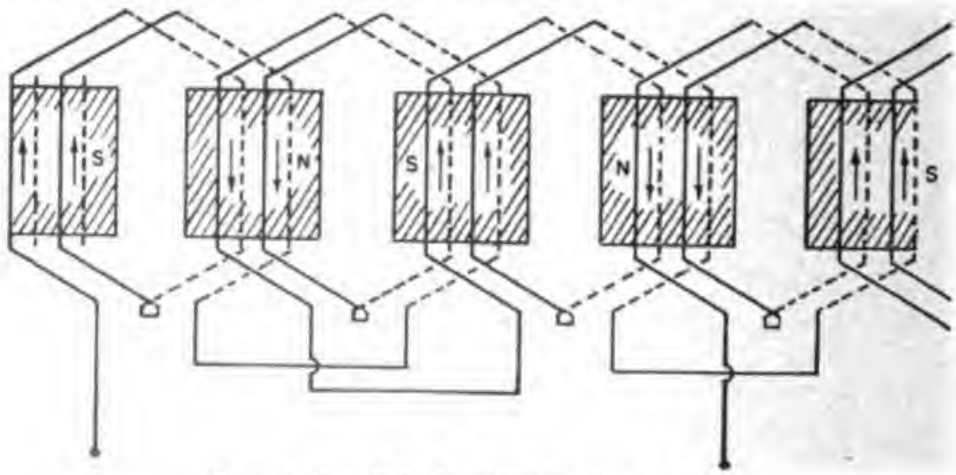
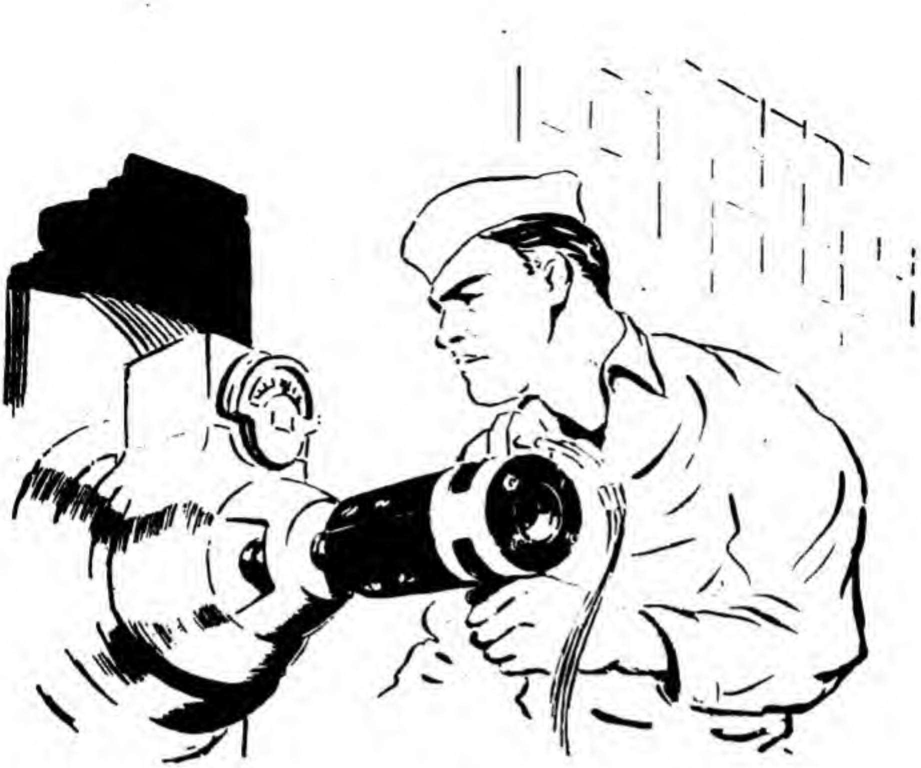


Figure 96.—Whole-coil, two-layer winding.

Also, in order to obtain commutation without sparking, you had to use MANY coils of a FEW turns each. Since the alternator has no COMMUTATOR, your problem is much simplified. An alternator has but few coils as compared to a d-c generator of similar size, and these coils are usually connected in series. Once you've understood the principles of d-c armature windings, you'll have no trouble laying out windings for a-c machines.

In figure 96, you see a single-phase, two-layer whole-coil winding. This winding is for a four-pole machine. There are two slots per pole. This winding is similar to those used on the a-c winding of Naval aircraft generators.



CHAPTER 7

MOTORS AND GENERATORS

A-C AND D-C MACHINES

Several types of rotating machines for use with both a-c and d-c power are already familiar to you. You'll find the operation of several other types of machines not mentioned before, discussed in this chapter. These machines are the INDUCTION MOTOR, the SYNCHRONOUS MOTOR, and the AMPLIDYNE GENERATOR. The induction motor, and the synchronous motor are ALTERNATING-CURRENT machines, while the amplidyne generator is a DIRECT-CURRENT machine.

The applications of these machines on aircraft vary from supplying electrical power to the aircraft for lights, engine-starting, and radio equipment, to the smaller motors and generators that supply power to the flight instruments.

ALTERNATORS—WHAT THEY ARE

The generation of an emf depends only on the relative motion of a conductor and a magnetic field, therefore the armature OR the field in all generators may rotate. In general, all commercial alternators have a stationary armature and a rotating field. Alternator armature and field winding are very much like those of the direct-current machines.

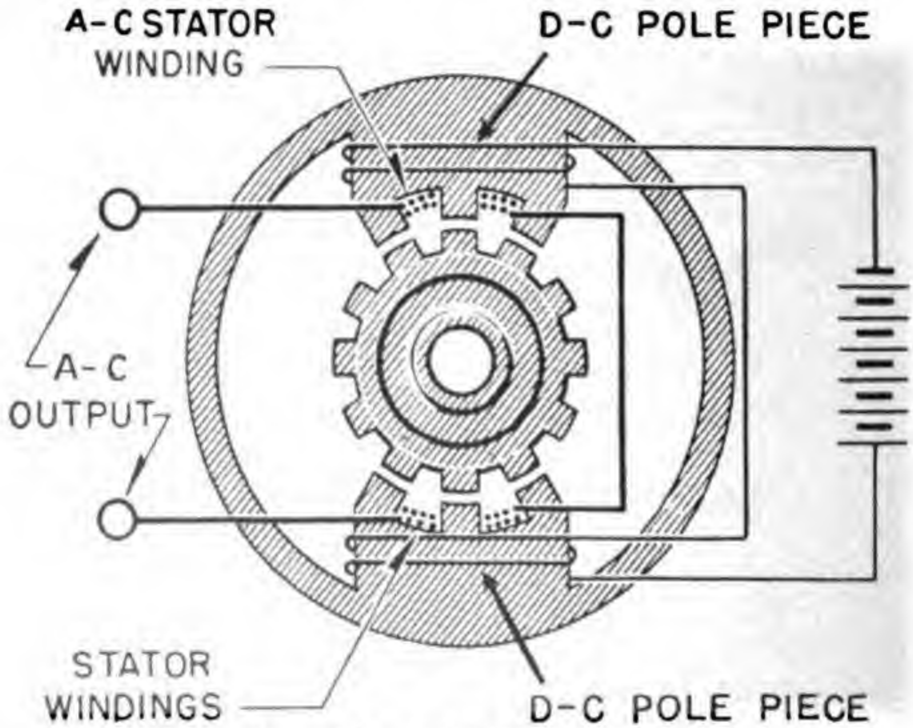


Figure 97.—Induction alternator.

In the alternator armature windings, however, the connections are made directly to the power load without a sliding contact. You bring the field connections out to two slip rings on the shaft of the rotor. Then connect these fields to a d-c supply by carbon brushes.

INDUCTION ALTERNATOR

For aircraft power supplies from the combination a-c, d-c generator, you use a single-phase induction-type alternator.

Look at figure 97 for the construction of the induction alternator. The a-c armature windings are in slots in the surface of the d-c pole pieces. The rotor is slotted but has no windings. The slotted rotor turns in the magnetic field, produced by the d-c field windings. This varies the reluctance of the magnetic path. Remember what RELUCTANCE is? It's the resistance of a material to the passage of magnetic flux. This varying reluctance causes a change in the strength of the magnetic field and produces an alternating emf in the a-c windings. You can see that the operating principles of this alternator, and of the NEA-3 aircraft generator, are similar to that of the magneto.

THREE-PHASE ALTERNATOR

The only places you'll find three-phase alternators in aircraft are in electrical instruments. The schematic diagram of a STAR-AND-DELTA-connected three-phase alternator is given in figure 98. The small amount of power these alternators must produce makes field windings and sliding contacts for the windings unnecessary. The fields of these alternators are four-pole permanent magnets with high field strength.

In the modern alternator, synchronous motor, and induction motor, you place the armature windings in

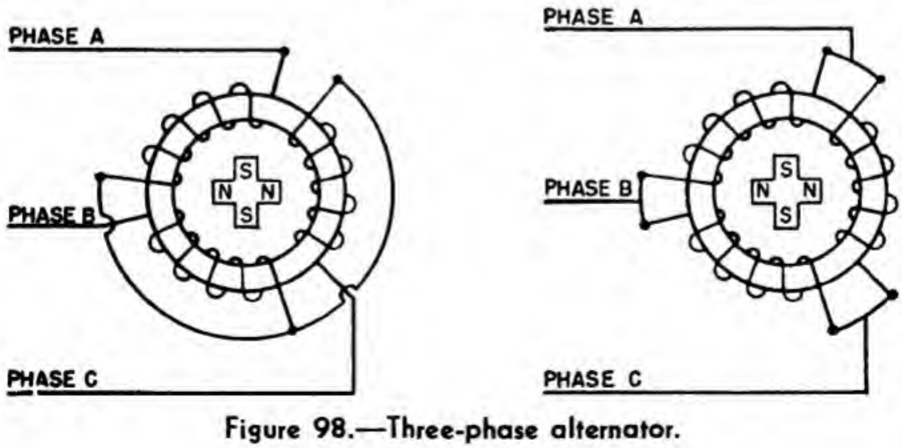


Figure 98.—Three-phase alternator.

a slotted stator frame. On low-power alternators, you can use permanent magnets as a field supply. On high-power alternators, requiring field windings, you use formed coils wound on the pole pieces. Ring windings are used for the sake of simplicity.

INDUCTION MOTOR

The INDUCTION MOTOR is the most widely used type of alternating-current motor. This is due to

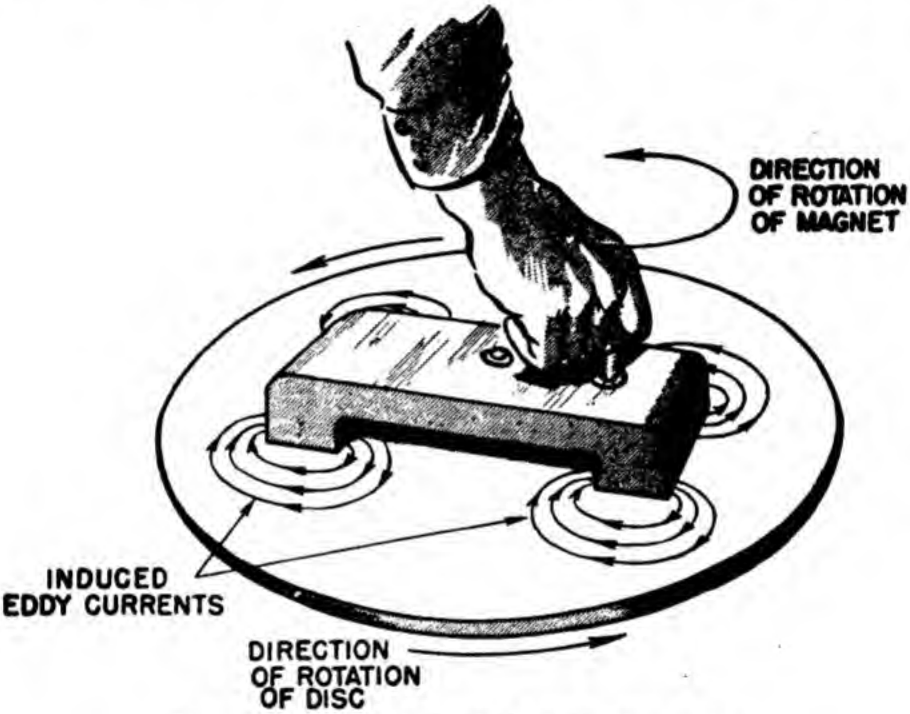


Figure 99.—Principle of the induction motor.

its simplicity and sturdiness. It doesn't have a COMMUTATOR, and its operating characteristics are well-adapted to constant-speed work.

You see the principle of the induction motor in figure 99. A metal disk is placed upon an axle and is free to rotate. The disk can be made of any conducting material, such as iron, copper, or aluminum. A magnet also free to rotate, is placed upon the same axle. The ends of the magnet are bent so that its magnetic field cuts through the disk. When

you rotate this magnet, its flux cuts through the disk and induces currents in it. As these currents find themselves in a magnetic field, they tend to move across this field. The direction of force developed between these currents in the disk and the magnetic field producing them will be such that the disk tends to follow the magnet.

The disk can never turn as fast as the magnet. If the disk did reach the rotation speed of the magnet, the disk would not be cut by the lines of force of the magnet. The disk current, would then become zero and no turning effect or TORQUE would develop. Since the disk cannot turn as fast as the magnet, a difference always exists between the speeds of the two. This difference is called the REVOLUTIONS OF SLIP.

You can use a cylinder instead of the disk. If the frame carrying the magnet poles is turned by an engine or other mechanical means, the currents induced in the cylinder will cause the cylinder to rotate.

AND WHAT ARE ROTATING FIELDS?

The ROTATING FIELDS of an induction motor may be produced by POLYPHASE currents. These rotating fields are produced entirely by ELECTRICAL means. There is NO mechanical rotation of the pole pieces themselves.

You see the simplest type of rotating field in figure 100. Each winding consists of two coils spaced opposite each other. Each section occupies approximately one-fourth of the winding space on the ring. Study the diagrams in figure 100 carefully, and you will see how the magnetic field rotates.

As you change the direction of the current through these windings you also change the polarity of the windings. Since there are two windings acting in conjunction with each other, the polarity of the main

field will depend upon the polarity of each winding. The arrow or vector below each diagram indicates the direction of the magnetic field in each case.

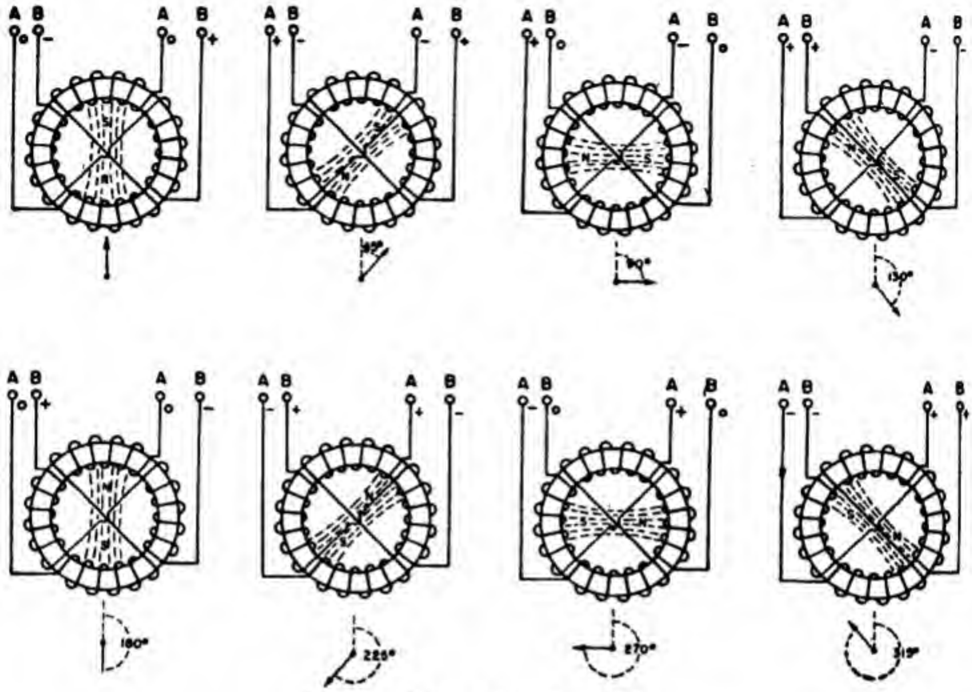


Figure 100.—Rotating fields.

This ring doesn't have to use two separate windings. You can use a continuous winding, tapped at four equidistant points, as in figure 101. Two of the taps, spaced opposite each other, are connected to phase A, and the other two to phase B. A winding of this type is a two-phase winding.

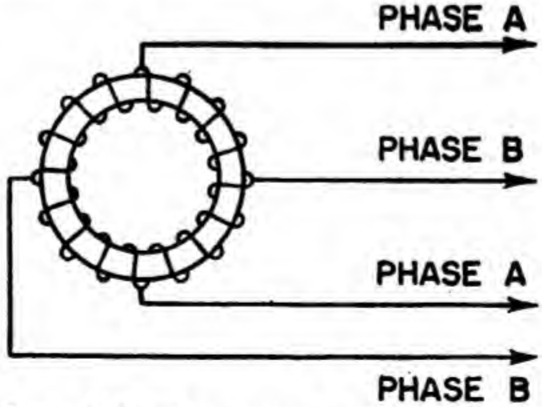


Figure 101.—Continuous tapped winding.

Figure 102 shows you a three-phase star- and delta-connected winding for an induction motor.

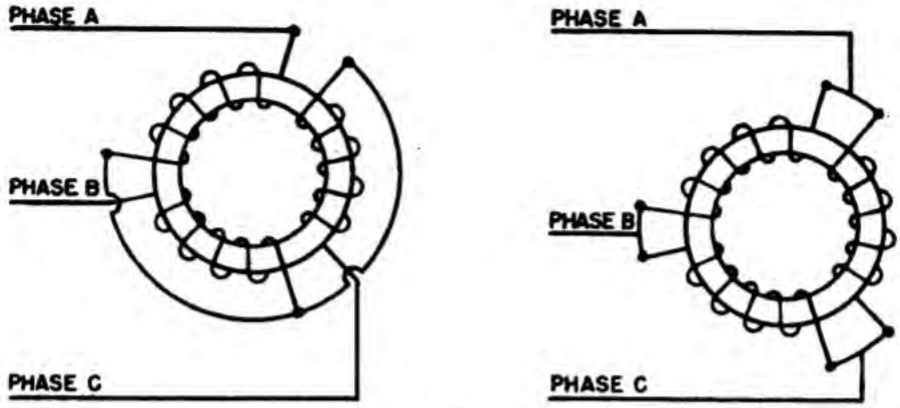


Figure 102.—Three-phase induction motor.

SYNCHRONOUS SPEED AND SLIP

You remember that the frequency of an alternating voltage depends upon the number of poles on the rotor and the speed of rotation of the alternator field. This frequency was—

$$f=\frac{PV}{60}$$

f = frequency in cycles per second.
V = speed of rotation in revolutions per minute (rpm).
P = number of pairs of poles on rotor.

If you use an alternating voltage to supply power to a motor, you'll find that the rpm of the motor would depend upon the number of poles in the machine and the frequency of the a-c voltage. The speed, V, is—

$$V=\frac{60\,f}{P}$$

The speed, V, of the rotating field of the motor is called the SYNCHRONOUS SPEED of the motor. Com-

mon synchronous speeds for commercial motors at 25 and 60 cycles per second are listed in this table.

Poles	V in RPM	
	f=25	f=60
2	1,500	3,600
4	750	1,800
6	500	1,200
8	375	900
12	250	600

If you place an armature whose conductors form closed circuits in a rotating field, the armature will develop torque because of the reaction between the field produced by the induced currents in the armature and the rotating magnetic field. This is the principle of an induction motor.

Again, as in figure 99, the armature can never reach the rpm of the rotating field. If it did, the cutting of conductors by flux would cease and no torque would be developed.

The difference between the speed of the rotating field and that of the rotor is called the REVOLUTIONS OF SLIP of the motor. For example, if you have a two-pole motor operating on 60-cycle current and running 3,500 rpm, the revolutions of slip would be the difference between 3,600 (synchronous speed) and 3,500, or 100 rpm.

You'll usually express the slip as a fraction of the synchronous speed. So—

$$s=\frac{V-V_1}{V}\times 100$$

s=percentage of slip

V=synchronous speed

V_1=actual speed of motor

In the example above, the percentage of slip would be as follows—

$$S=\frac{V-V_1}{V}\times 100$$

$$=\frac{3{,}600-3{,}500}{3{,}600}\times 100$$

$$=\frac{100}{3{,}600}\times 100=2.8 \text{ percent}$$

SYNCHRONOUS MOTORS

You already know that d-c motors and generators are similar in construction. They differ only in the provisions made for neutralizing armature reaction. If you apply d-c voltage to the terminals of a d-c generator, it will rotate as a motor.

Alternators and synchronous motors are also similar in construction. If you apply a-c voltage to the alternator terminals, the machine will operate as a synchronous motor.

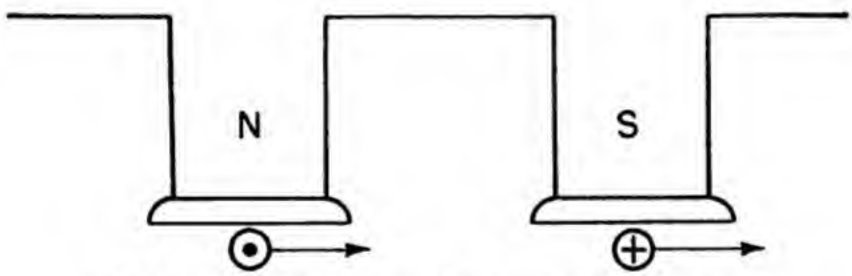


Figure 103.—How a synchronous motor operates.

HOW THEY WORK

In figure 103, you see a conductor under a north pole, carrying a current flowing toward you. Because of motor action a torque is developed. This tends to drive the conductor from left to right. If the current in this conductor is alternating, it will reverse its direction during the next half cycle, and the torque will be from right to left. The net torque over a

full cycle of a-c current is then zero. This is the condition in a synchronous motor when it is standing still.

But, if you move this conductor under a south pole for the second half of the cycle, the resulting torque would still be from left to right. This conductor would tend to continue to move from left to right. In a synchronous motor with a rotating-armature, you must move a given conductor from one pole to the next in each half-cycle if the machine is to operate continuously. If your machine uses the ROTATING FIELD, instead of the rotating armature, you must move one of the poles past the given conductor each half-cycle.

The field produced by alternating current in the armature will rotate at a synchronous speed. This field will lock in with the steady field of the rotor and make the rotor move at the speed of the synchronous field. So, the speed of a synchronous motor will be constant if the frequency of the applied emf is constant.

SYNCHRONOUS MOTORS IN AIRCRAFT

You use synchronous motors in airplanes only to operate certain instruments. In figure 104, you see the schematic diagram of a synchronous motor used

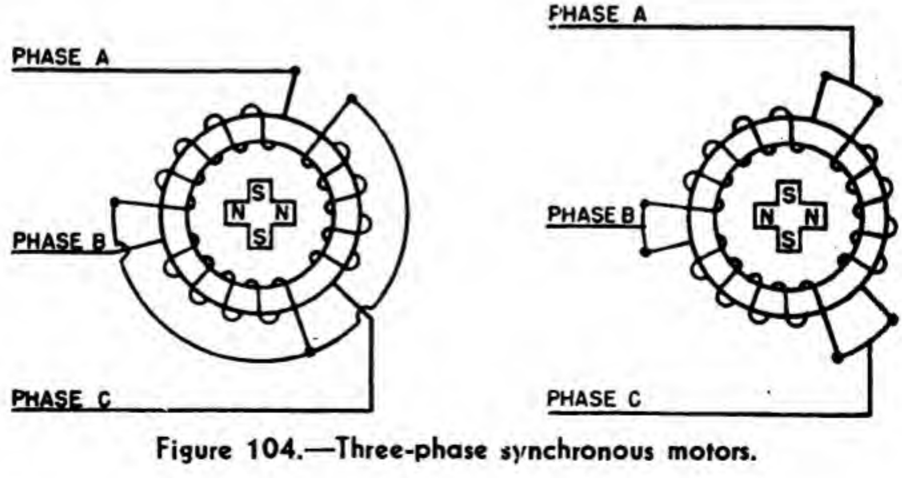


Figure 104.—Three-phase synchronous motors.

in an aircraft instrument. You get the power for this motor from a three-phase alternator. Like the alternator, the constant fields are produced by permanent magnets to decrease weight and allow the use of electricity in instruments.

AMPLIDYNE GENERATOR

Engineers and electricians have hunted a long time for a fast, reliable way to amplify and control power. They really made progress when they found that they could control the speed of a d-c motor by putting a rheostat in its field circuit. After this discovery they made rapid progress and have developed numerous control amplifiers. Another method of controlling and amplifying power is grid control of power tubes and rectifiers.

The newest power control amplifier is the AMPLIDYNE. The amplidyne has a large amplification factor, speed of response, and is reliable. You'll use the amplidyne generator in aircraft to supply power to turret-control motors. High speed of response and high amplification make it useful for this job. Using the amplidyne, you can control very large power in one circuit with a very small power in another. The ratio may be as high as 1,000 to 1. The amplidyne generator combines certain electrical characteristics of both vacuum tubes and rotating electrical equipment.

WHAT MAKES THE AMPLIDYNE TICK?

If you apply a field to a simple d-c generator, as in figure 105, and rotate the armature at a constant speed, you will generate an emf which is proportional to the field flux. If you apply this potential to an outside load, a current will be forced to flow. The path of the current will be through the load and the armature as indicated in figure 105. The current

will be proportional to the voltage generated and INVERSELY proportional to the resistance of the load.

The current flowing through the armature will produce a magnetic field around the armature conductors. The strength of the field will be proportional to the amount of armature current or load

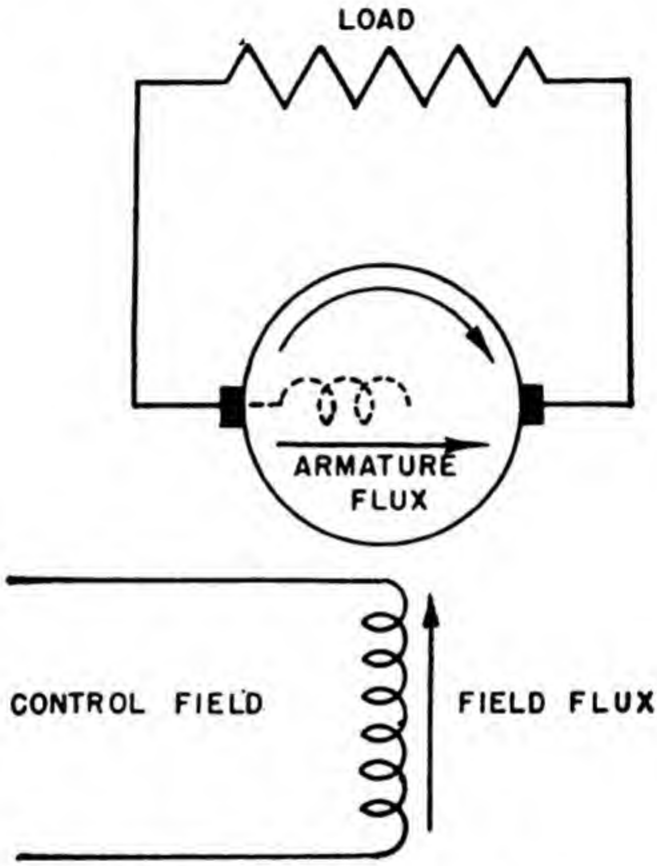


Figure 105.—D–C generator.

current. This magnetic field is called ARMATURE FLUX and will always be at RIGHT ANGLES to the CONTROL FIELD FLUX. Even though the armature is continuously rotating, this armature flux field will remain STATIONARY. The effect of the armature flux is called ARMATURE REACTION. In an ordinary generator, this reaction is a nuisance from the standpoint of commutation. You neutralize it by commutating interpoles or compensating windings. But

in the amplidyne generator, you put the armature flux to work.

In figure 106 (*A*), you make the control field large enough so that the full-load current of the generator will flow and a large armature flux will be produced. If you decrease this field, there will be little or no voltage generated across the load, and no load current will flow. If you have no load current, you have no armature flux. This action is shown in figure 106 (*B*).

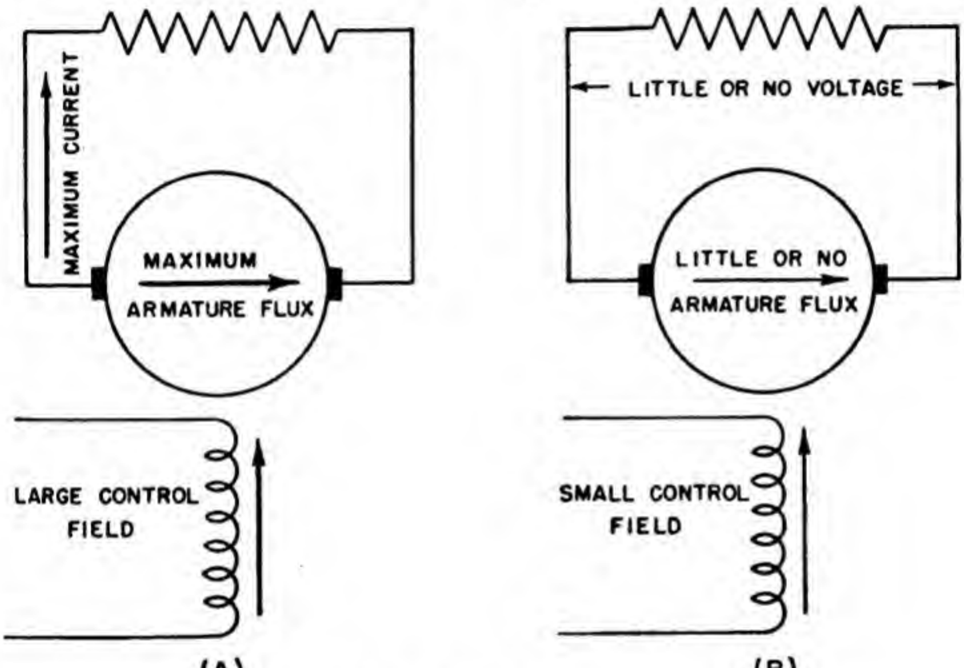


Figure 106.—Effects of large and small control field.

Now make the load resistance very small by short-circuiting the armature as in figure 107. A SMALL FIELD FLUX will produce full-load armature current and a large armature flux. Since the field flux builds up to only a low value and since the resistance and reactance of the short-circuited armature are very low, this full-load current will be obtained in a very short time.

Next, add two poles and brushes to a simple generator, as in figure 108. These brushes are called

the LOAD AXIS. The SHORT-CIRCUIT AXIS FLUX of the armature will be at RIGHT ANGLES TO THE LOAD AXIS. Because of this, the short-circuit axis flux will produce a voltage across the terminals of the load axis. This load axis voltage will be proportional

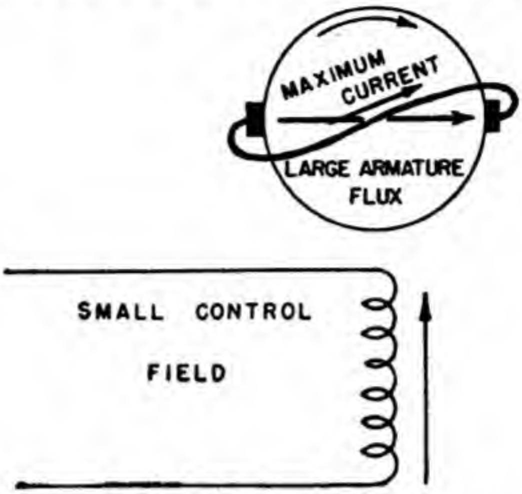


Figure 107.—Short-circuited armature.

to the amount of short-circuit current that produces the short-circuit flux. Since the current flowing in the short-circuit axis is MAXIMUM LOAD CURRENT, the voltage across the load axis will be full-load voltage. A generator of this type is called a CROSS-AXIS EXCITED GENERATOR.

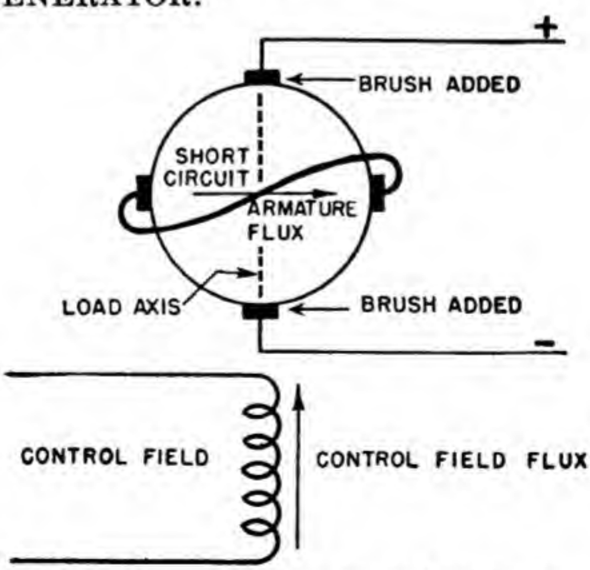


Figure 108.—Cross-axis excited generator.

Now, to convert the cross-axis excited generator into an AMPLIDYNE GENERATOR. If you connect a load to the load-axis brushes, the load current which flows will produce an armature flux which opposes the initial control field. This would mean that the field flux has to be strong enough to overpower this load-axis armature flux. However, you can overcome this effect by making the load current flow

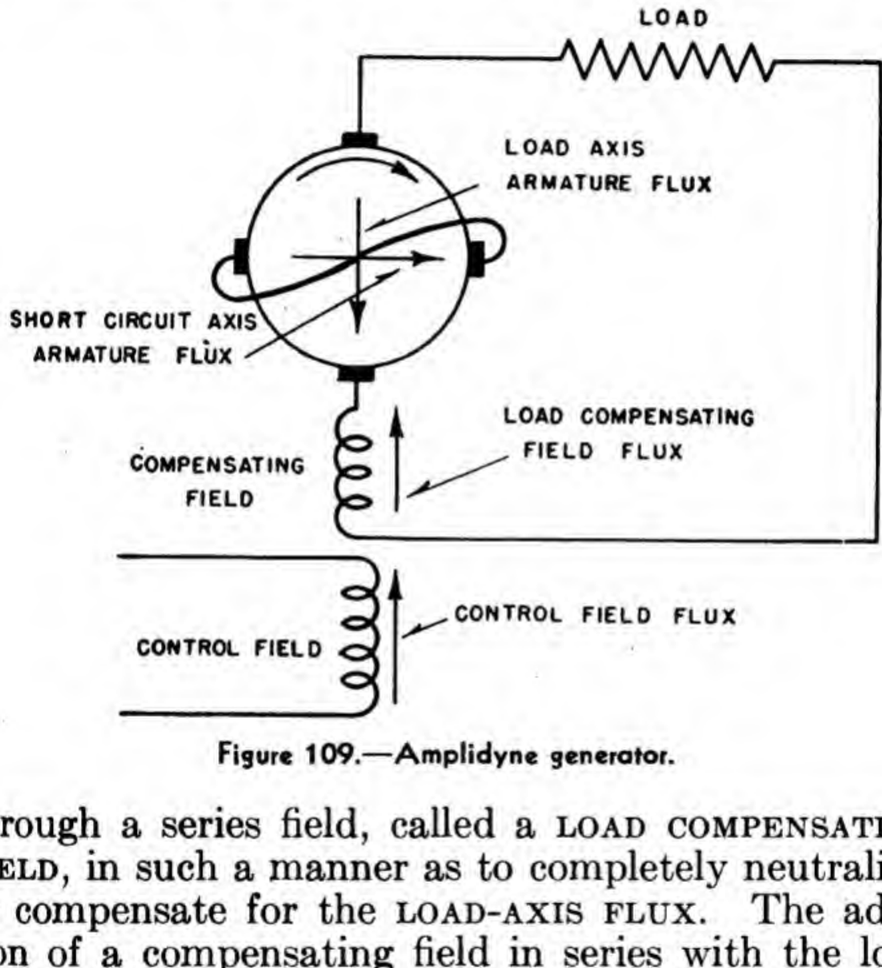


Figure 109.—Amplidyne generator.

through a series field, called a LOAD COMPENSATING FIELD, in such a manner as to completely neutralize, or compensate for the LOAD-AXIS FLUX. The addition of a compensating field in series with the load axis converts the cross-axis excited generator into an amplidyne.

The connections of the LOAD COMPENSATING FIELD and the relation among the different magnetic fields of the amplidyne are shown in figure 109. By using this compensating field, the control field needs to produce only enough field flux (and resulting emf)

to overcome the resistance in the SHORT-CIRCUIT AXIS. This arrangement produces a high-speed motor response.

CHARACTERISTICS OF THE AMPLIDYNE

The number of ampere-turns required to produce the control field flux is only the small number needed to force this small field flux across the small air gap and through the magnetic structure of the machine. Since the resistance of the short-circuit axis and the air gap vary only slightly with various sizes of amplidyne generators, there is only a slight variation in the control or field flux required. You can see that the control power required may practically be considered a constant value, regardless of the size of the amplidyne.

And here is the secret of the amplidyne—The voltage across the brushes of the SHORT-CIRCUIT AXIS is very SMALL in comparison to the MAXIMUM OUTPUT VOLTAGE of the machine. Only a small amount of field flux is needed to generate the small voltage required to produce maximum current in the short-circuit axis. This small current in turn causes maximum flux and maximum voltage at the load axis. Although you have only one set of conductors on the armature of an amplidyne, you have TWO isolated sets of brushes. One set of brushes commutates SHORT-CIRCUIT CURRENT and the other set commutates LOAD-AXIS CURRENT. The short-circuit axis current is approximately equal to the load-axis current. The voltage across the short-circuit axis, however, is negligible.

An amplidyne is really two machines in one. Consider the control field as the field of a low-voltage-high-current exciter, the armature of which is connected to a low-voltage high-current field on a second exciter. The armature of the second exciter, however, is wound so as to give a higher voltage.

To practice economy, you can sometimes increase the amplification of an amplidyne by increasing the short-circuit axis current. You can do this in two ways. FIRST METHOD—Add a SHUNT field in the short-circuit axis. This field, however, will be excited by connecting it across the load axis brushes. SECOND METHOD—Add a SERIES field which is ex-

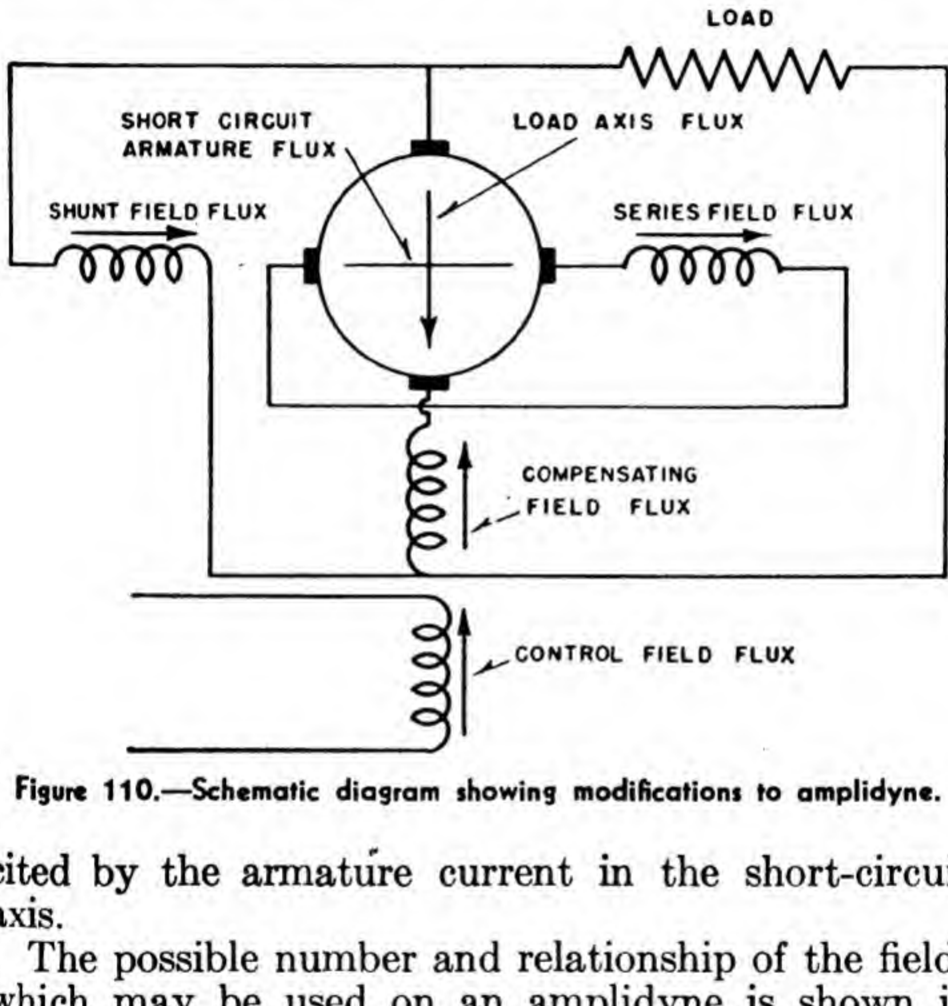


Figure 110.—Schematic diagram showing modifications to amplidyne.

cited by the armature current in the short-circuit axis.

The possible number and relationship of the fields which may be used on an amplidyne is shown in figure 110. You seldom use all these fields on one machine. No machine has yet been built with both self-excited shunt and series fields.

From this it can be seen that an amplidyne has essentially only two fields. These two are the CONTROL field and the LOAD-COMPENSATING field.

CHAPTER 8

POWER TRANSFORMERS

DESIGN AND CONSTRUCTION

Suppose you are out in the wilds of nowhere, and are handed a badly damaged transformer to rebuild. You can't tell what size of wire was used nor how many turns there were on each coil. Can you rebuild it? Of course you can. Your problem is easily solved if you can get the data on (*a*) voltage frequency of the a. c.; (*b*) primary voltage; (*c*) secondary voltage and; (*d*) either secondary or primary current.

TYPES OF TRANSFORMERS

You'll run into two types of transformers—classified by the arrangement of the coil and the core. They are the CORE type and the SHELL type, both shown in figure 111. Power transformers are usually of the air-cooled shell type, and the transformers you'll run into are usually designed for 25, 50, 60, and 500-cycle operation.

CORE MATERIAL

Silicon steel and soft iron are used for core material in most power transformers. Soft iron is used in the cheaper transformers. Silicon steel is a better core material. When silicon steel is used, the required cross-sectional area of the core is less for a given power and frequency.

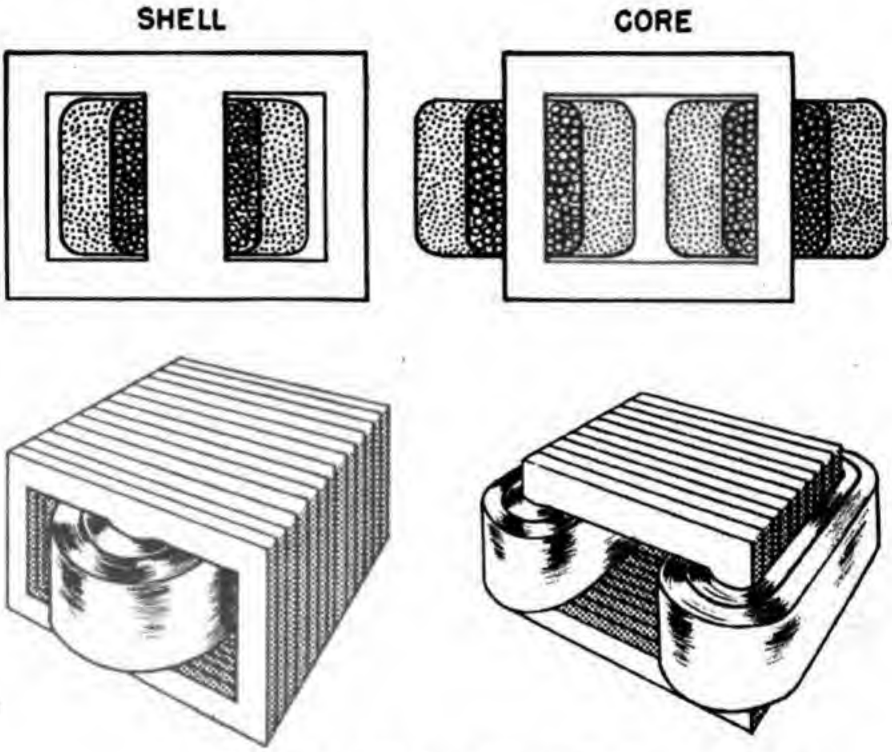


Figure 111.—Transformer types.

The core is built up of LAMINATIONS to reduce eddy currents. In order to accomplish this, the laminations must be insulated from each other. When core material is rusty, the coating of rust acts as a fine insulation to reduce eddy currents to a minimum. However, it does no harm to coat each lamination with insulating varnish. Always varnish NEW laminations.

Use a file to remove the burred edges from each core lamination. Filing prevents contact between

edges of adjacent laminations. Such contact would form a short-circuit path for eddy currents.

Losses can be caused by the current set up in a closed metal circuit located in the path of the flux. One of these circuits might be the metal bolts and cross pieces used to hold the transformer together. To some extent, this closed circuit would have the same effect as a shorted turn in the secondary, and would cause poor regulation and high losses. Break this circuit at some point. You can do this by placing an insulating washer and ferrule at that point where the bolt goes through the iron cross pieces.

REGULATION

The REGULATION of a transformer is defined as the drop in secondary voltage, from no-load to full-load, in terms of full-load, and is expressed in percentage.

$$\frac{(\text{No-load voltage}-\text{Full-load voltage})(100)}{\text{Full-load voltage}}=\text{Regulation, in }\%$$

If a certain transformer has a terminal voltage of 100 volts across the secondary at no-load, and 90 volts at full-load you can find the regulation by using the formula—

$$\frac{E_{nl}-E_l}{E_l}=\frac{100-90}{90}=0.11\text{, or 11 percent.}$$

Transformer regulation is computed at unity power factor. A circuit has unity power factor or a power factor of 1.0 when it contains RESISTANCE ONLY. If the circuit contains RESISTANCE AND INDUCTANCE, it will have a power factor of less than 1.0. The unity power factor may be obtained through resistance loading.

Poor regulation is usually caused by excessive magnetic leakage, or excessive resistance of the windings for the load. Magnetic leakage is mainly dependent upon the relative positions of the primary and

secondary windings on the core. This in turn is dependent upon the design of the transformer.

Look at figure 112 for various arrangements of windings and cores. Arrangements *A* and *B* are particularly poor. The primary has been placed on one leg, and the secondary on the other. The wasted window space makes the magnetic path much longer than necessary. This in turn increases the magnetic leakage. The regulation of such a transformer would be very poor.

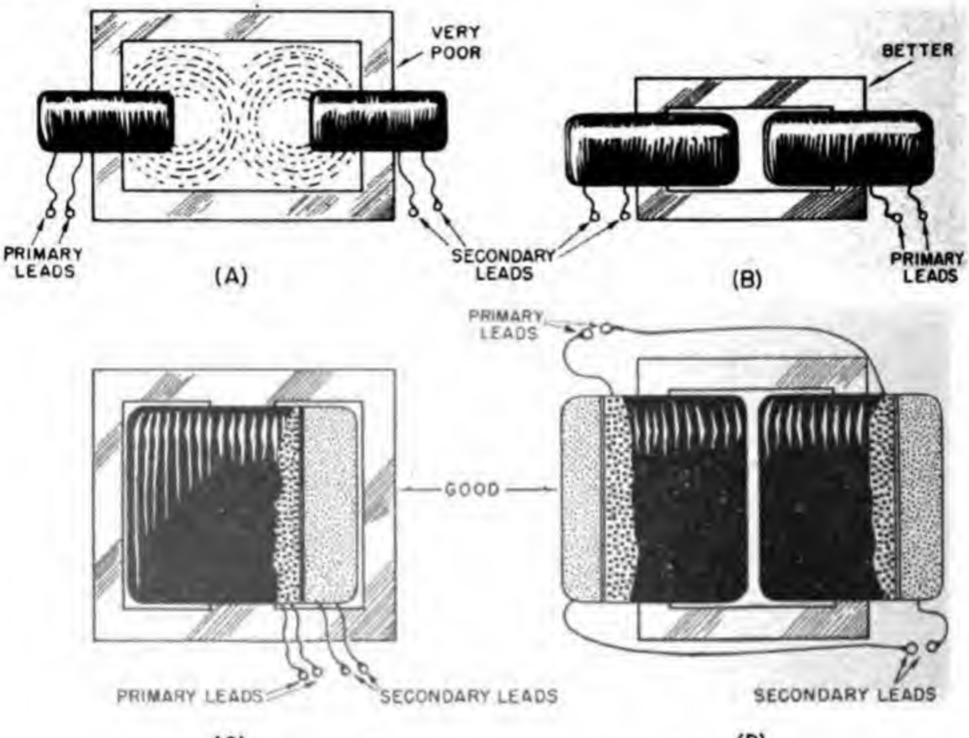


Figure 112.—Arrangement of core and windings.

Arrangements *C* and *D* are standard for SHELL and CORE type transformers. Here the secondary is wound over the primary, and the magnetic path is very short. A well-designed transformer of this type can be made to approach 98 percent efficiency.

WHAT ABOUT FREQUENCY?

Generally speaking, you can use a transformer at a frequency higher than that for which it is designed,

without making any changes in the transformer. As an example, a transformer designed for 25-cycle operation, 110-volt input and 12-volt output, may be used on 60 cycles, provided that you keep the input voltage at 110. The output voltage would remain very nearly the same for each frequency and approximately the same power could be taken from the secondary.

You cannot use a transformer on a LOWER frequency than it was designed for, without decreasing the input potential. This results in a lower output voltage and wattage rating. Assume, for example, that you want to use a transformer rated at 500 watts, 110 volts, 60 cycles, on a 25-cycle line.

From table I, at the end of the chapter, you'll find that input voltage can be only 78 percent of the original value. The output voltage will be reduced by the same percentage, or to about 86 volts. The wattage rating will also be decreased to 78 percent of 500 watts or 390 watts.

The cross-sectional area or C. S. A., of the core is that area of the core measured in a slice cut across the magnetic field. It is also measured at the point where the cross sectional area is the least. In a core-type transformer, the area is the same at all parts of the core. In the shell-type transformer, the C. S. A. of the center leg is equal to the sum of the areas in the outer legs. The area to be considered in this case is the smallest area, or the center leg, which carries the full amount of magnetic flux.

You can vary the size of the core over wide limits, yet your transformer will be entirely satisfactory. Table II is given as a guide. This table shows the average C. S. A. required in a core for different power ratings. You will see that the C. S. A. of a core must be increased as the power output of the transformer is increased. If you need a transformer with a larger power output it will have a greater C. S. A.

The value of C. S. A. you use will generally depend on the type of used core material you have lying around.

HOW MANY TURNS PER VOLT?

The total number of turns required for the primary winding depends on the voltage you will apply to the primary. It also depends on the cross sectional area of the core and the type of core material you use. The number of turns per volt needed for a core 1 square inch in C. S. A. is listed in table III, for different core materials.

Having found the required core area, you can find the turns per volt by referring to table III. If your required core area is larger than 1 square inch, you must divide these readings by the numerical value of the required C. S. A. In the case of a transformer having a required C. S. A. of two square inches, you would divide the readings taken from the table by two. If the required core area happens to be 0.5 square inch, divide the readings in the table by 0.5.

When you have found the number of turns per volt, it is easy to calculate the number of turns required on both primary and secondary windings. The primary voltage is known and the desired secondary voltage is also known. By applying the following formulas, you can figure the number of turns on each winding.

$$\text{Number of Primary Turns} = \left[\text{Number of Turns per Volt}\right] \times \left[\text{Number of Primary Volts}\right]$$

$$1. \quad N_P = (T/v)(E_P)$$

The number of turns-per-volt is a constant which holds for both primary and secondary windings. Hence, the following formula applies for determining the number of turns in the secondary winding.

$$\text{Number of Secondary Turns} = \left[\text{Number of Turns per Volt}\right] \times \left[\text{Number of Secondary Volts}\right]$$

$$2. \quad N_s = (T/v)(E_s)$$

In the case of the secondary winding, it is customary to add 3 percent in the number of turns to compensate for the IR drop in the windings under load.

WHAT WIRE SIZE?

You generally select the wire size according to the power output, but more specifically by the current in the winding. When you are redesigning a used transformer, the window space is also a factor.

The power input of the transformer (at unity P. F.) is equal to the product of the primary voltage and primary current. Since you know the power input and primary voltage, you can figure the primary current by substitution in the following formula.

$$\text{Primary Current} = \frac{\text{Watts Input}}{\text{Primary Voltage}}$$

$$3.\quad I_p = \frac{W_i}{E_p}$$

You also know the transformer output. Hence, you can use a similar relationship to determine the secondary current.

$$\text{Secondary current} = \frac{\text{Watts Output}}{\text{Secondary Voltage}}$$

$$4.\quad I_s = \frac{W_o}{E_s}$$

When you've found the current in both primary and secondary, you select the wire size by referring to table IV. In selecting the wire size, you must consider the type of service the transformer will operate under. For intermittent duty, a cross-sectional area of 1,000 circular mils (CM) is required for each ampere. For continuous duty, a C. S. A. of 1,500 CM per ampere should be used.

NOW DESIGN A TRANSFORMER

You are to re-design a used transformer having a silicon steel core with a C. S. A. of three square

inches and a window opening of 2 inches by 4 inches to the following specifications.

Power Output .	500 watts
Power Input (Power Output + 10%)	550 watts
Primary Voltage	110 volts
Secondary voltage	500 volts
Frequency	60 cycles
Duty	Continuous

CORE AREA. A look at table II shows that you need a C. S. A. of 3.2 square inches for an output of 400 watts. Since some variation is permissible, you'll be safe in using the original core with a C. S. A. of 3 square inches.

TURNS PER VOLT. By referring to table III, you get a value of 6.3 turns per volt for a silicon steel core 1 square inch in C. S. A. at 60 cycles. Since the C. S. A. of the core to be used is 3 square inches, you must divide this reading by 3.

$$\text{Turns per volt } (T/V) = \frac{6.3}{3} = 2.1 \text{ turns}$$

Next, use Formulas 1 and 2 to get the number of turns in both secondary and primary windings.

$$\begin{aligned} N_p &= (T/v)(E_p) \\ &= (2.1)(110) = 231 \text{ turns} \\ N_s &= (T/v)(E_s) \\ &= (2.1)(500) = 1{,}050 \text{ turns} \end{aligned}$$

Add 3 percent to the number of turns in the secondary winding to allow for an IR drop and other losses.

$$N_s = 1{,}050 + 0.03\ (1{,}050) = 1{,}081.5 \text{ turns}$$

CURRENT. To obtain data for wire size, use Formulas 3 and 4 to figure the full-load current in both primary and secondary windings.

$$I_p = \frac{W_i}{E_p} = \frac{550}{110} = 5 \text{ amperes}$$

$$I_s = \frac{W_o}{E_s} = \frac{500}{500} = 1 \text{ ampere}$$

C. S. A. Since the transformer is to be designed for CONTINUOUS DUTY, you will use a wire size based on 1,500 CM/ampere.

WIRE SIZE. You can determine the wire size to be used in both secondary and primary winding by referring to table IV. For the primary winding, #11 B. & S. with a C. S. A. of 8,234 CM has the nearest value to the required value of 7,500 CM.

For the secondary winding, #18 with 1,624 CM is the nearest value. Odd size wires are not always stocked. Hence, you can use #10 for the primary winding and #18 for the secondary winding.

The window space required for each winding can be obtained by referring to Table V. This table lists the approximate number of turns per linear inch for various wire sizes and insulation. You will find that 9.2 turns of #10 ESCC (Enamel Single Cotton Covered) wire can be wound per LINEAR inch. By squaring 9.2, you can find the number of turns that can be wound per square inch of window space. You'll have to subtract approximately 10 percent from this figure to allow for insulation between layers of the winding. The following calculations determine the window space you'll need for the primary and the secondary windings.

PRIMARY WINDING

Turns per linear inch (#10)	$= 9.2$ turns
Turns per square inch	$= (9.2)^2 = 84.6$ turns
Allowance for insulation	$= 0.10\ (84.6) = 8.4$ turns
Turns per square inch	$= 84.6 - 8.4 = 76.2$ turns

The primary winding requires 231 turns. Since one square inch is required for 76 turns, the window area required for 231 turns can be obtained by dividing 231 by 76.

$$\frac{\text{Window Area}}{\text{(Primary)}} = \frac{\text{Total Primary Turns}}{\text{Turns per square inch}} = \frac{231}{76} = \frac{3 \text{ sq. in.}}{\text{(approx.)}}$$

SECONDARY WINDING

Turns linear inch (#18 SCC)	$=22.2$ turns
Turns per square inch	$=(22.2)^2=492$ turns
Allowance for insulation	$=0.10\ (492)=49$ turns
Turns per square inch	$=492-49=443$ turns

$$\frac{\text{Window area}}{\text{(Secondary)}}=\frac{\text{Total Secondary Turns}}{\text{Turns per sq. inch}}=\frac{1{,}081}{443}=2.4 \text{ sq. in.}$$

The total window space occupied by the windings is equal to the sum of the area required for each winding.

Total required window space = Primary area + Secondary area $=3+2.4=5.4$ square inches.

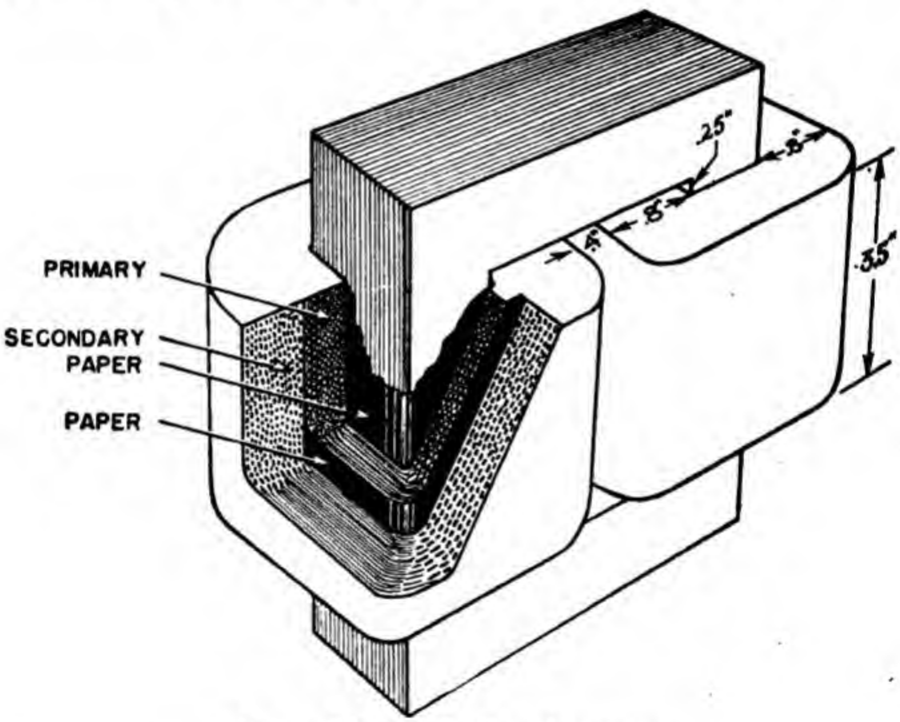


Figure 113.—Winding clearance.

If you look at figure 113, you will see that the ends of the windings are very close to the inside edge of the core sides. To prevent the possibility of FLASH-OVER, you need a certain amount of clearance at these points. This is particularly true of high-voltage transformers. This means that you must make the length of the winding less than the length

of the window space by an amount equal to twice the clearance, 0.25″, in figure 113. This spacing need not be more than ¼ inch for a 500-volt winding. In the core-type transformer shown, the secondary winding is in two sections. Since each section develops 250 volts, a spacing of ¼ inch is ample. If space is at a premium you can reduce this space to ⅛ inch.

In this case, the dimensions of the window opening are 2 inches by 4 inches. The area you need for the windings is 5.4 inches. The difference ($8-5.4=2.6$ sq. in.) is available to you for spacing between the primary and secondary windings and for clearance between all windings and the core sides.

If you make the clearance ¼ inch, the length of both windings becomes 3½ inches. You can find the over-all depth of both windings by the use of the formula which expresses the area of a rectangle in terms of length and width (depth).

$$A = LW$$

$A = 5.4$ sq. in., $L = 3.5$ inches, $W = ?$

Solving for W:—

$$W = \frac{A}{L}$$

$$W = \frac{5.4}{3.5} = 1.5 \text{ inches}$$

Since the total depth of the windings is only 1.5 inches, you can use the remaining ½ inch for insulation and space between the primary and secondary windings. A small amount of this will be used between the primary winding and core. This is a liberal allowance, but the space you need for winding may be more than you figured.

INSULATION BETWEEN WINDINGS. The amount of insulation between the primary and secondary wind-

ing is determined by the magnitude of secondary voltage and its application in the circuit. The insulation should be sufficient to withstand the full secondary voltage. Several layers of varnished cambric (Empire cloth) or oil silk will suffice. When you rewind a transformer with the original power rating, be sure to follow the manufacturer's insulating procedure and specifications.

INSULATION BETWEEN LAYERS. The insulation thickness between layers of a winding is determined by the voltage difference between layers. You know the length of a winding and the number of turns per inch. By multiplying these quantities you can find the number of turns in a layer. You can find the voltage across a single layer by dividing the total number of turns in the layer by the number of turns per volt. Calculation of the voltage per layer for this particular transformer is shown below.

SECONDARY WINDING

Number of turns per inch	$= 22.2$
Winding length in inches	$= 3.5$
Number of turns per layer	$= 22.2 \times 3.5 = 77$
Number of turns per volt	$= 2.1$
Volts per layer	$= \frac{77}{2.1} = 36.6$ v.

The first turn of one layer is opposite the last turn of the layer beneath. The voltage between these two turns is therefore twice the voltage of a single layer, or 74 volts. A single layer of paper or Empire Cloth will be sufficient in this case.

The voltage between layers of the primary can be determined in a similar way. It will be less than the voltage between layers in the secondary. Calculations will show it to be approximately 31 volts. Hence a single layer of paper or varnished cambric will suffice.

WINDING FORMS

You can wind the coils of the transformer directly on the core, although this is seldom done. Coils are usually wound on a wooden form having the same dimensions as the core. They are then removed from the wood form and slipped over the winding section of the core. The end laminations are then inserted to close the magnetic circuit.

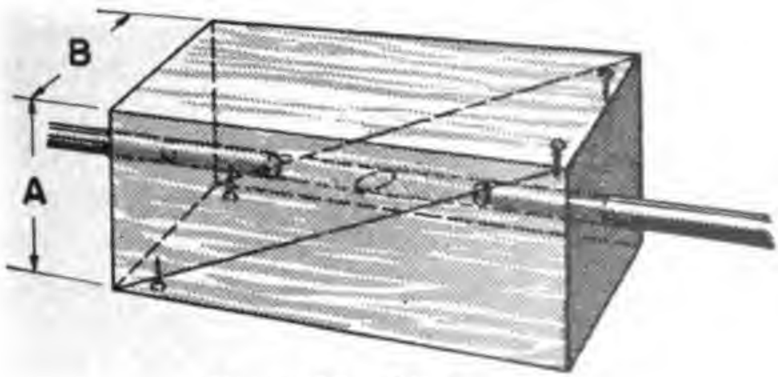


Figure 114.—Winding form.

A typical winding form is shown in figure 114. Dimensions *A* and *B* of the block are from $\frac{1}{16}$ to $\frac{1}{8}$ inch greater than the dimensions of the actual transformer core. By increasing the width and depth you can easily slip the completed winding on the transformer core. The length of the block is determined by the length of the winding. For this particular transformer, a block 5 inches long is sufficient. Put an axle through each end so you can chuck it in a lathe or hand drill.

If you made your winding on a solid block, it would be extremely difficult to remove it from the form. For this reason, cut the block diagonally to form two wedge-shaped blocks. Fasten these blocks together with two small wood screws at each end of the block. When you complete the winding, remove the screws and pull the two sections apart to release the winding.

WINDING THE COIL

Set up the winding form in a lathe. Use the back gears to rotate the form slowly enough to use a hand feed. Let the wire slip through a paper friction guard held between your fingers. You will need a fair amount of practice to get the wire to feed smoothly with no air gaps between turns. Remember that the hand you use to feed the wire should be at least two feet from the form. This is particularly true when you wind the secondary.

The PRIMARY coil is next to the core and must be wound on a firm insulating base. Wrap the winding form with several layers of Empire Cloth. One additional layer of thin cardboard will give needed rigidity. Wind the primary winding on this base with a single wrapping of paper between each layer. Linen tape and a small piece of spaghetti can be used to lock the first and last turns in place. For this particular transformer, ONE-HALF of the primary winding (116 turns) completes the first coil.

ONE-HALF of the secondary winding (541 turns) is then wound over the primary winding. Be sure to put enough insulation between the windings to withstand the full secondary voltage. Several layers of varnished cambric will be enough. Wind the secondary coil exactly the same way as the primary. Remove the finished windings from the form, and repeat the process to make the second set of windings.

There are many tricks to learn about making a good transformer winding. Try to spend a few days in the shop, working under the guidance of an experienced man. Your first attempt at winding a coil may be very crude, but with practice you can make a transformer comparable to a factory product. In the actual construction of the transformer, practice is the principal factor.

IMPREGNATION

Waterproof the coils by dipping them in a solution of hot paraffin and beeswax. This is very effective in tropical climates where excessive moisture may be encountered. Do NOT use shellac unless you can bake the coil in an oven. After impregnation, assemble your transformer. Take care not to damage the coils during the assembly.

TABLE I

TRANSFORMER DESIGNED FOR FREQUENCY OF—	PERCENT OF ORIGINAL PRIMARY VOLTAGE THAT CAN BE USED AT OTHER THAN DESIGNED FREQUENCIES				
	25 CYCLES	50 CYCLES	60 CYCLES	500 CYCLES	800 CYCLES
800 cycles	37	45	48	88	100
500 cycles	42	52	55	100	115
60 cycles	78	95	100	185	210
50 cycles	82	100	105	195	220
25 cycles	100	122	130	240	275

Values given above are slightly high for a core made of soft iron, but are very conservative for silicon steel. They are a compromise suitable for most cases.

TABLE II

SIZE OF CORE

Approximate (in square inches) for various power ratings. (Variations either way are acceptable within limits.)

POWER OUTPUT (WATTS)	FREQUENCY			
	25	50 or 60	500	800
	Sq. In.	*Sq. In.*	*Sq. In.*	*Sq. In.*
200 or less	1. 8	1. 5	0. 9	0. 6
400	4. 0	3. 2	2. 0	1. 25
1000	7. 0	5. 4	3. 4	2. 1
2000	11. 0	9. 0	5. 7	3. 5
3000	15. 0	12. 0	7. 5	4. 7
5000	20. 0	16. 0	10. 0	6. 25

TABLE III

TURNS PER VOLT

Required on individual windings wound on a core have a cross sectional area of ONE SQUARE INCH (Conservative Values).

(1)	(2)	(3)	(4)
FREQUENCY	SILICON STEEL	SOFT IRON	Material not identified. *COMPROMISE.*
25	8. 5	11. 0	10. 0
50	6. 7	9. 5	8. 2
60	6. 3	9. 2	7. 8
500	4. 3	5. 6	4. 9
800	2. 6	5. 1	3. 0

TABLE III-A

CHOKE TABLE FOR TRANSMITTER POWER SUPPLY UNITS

These values are based approximately on high grade silicon steel cores with total air gaps as given. Air gaps indicated are the total of all gaps.

CURRENT MA	WIRE SIZE	NR. TURNS	LB. OF WIRE	APPROX. CORE (AREA)	AIR GAP	WT. OF CORE
200	27	2000	1. 5	1.5 x 1.5″	3–32″	1 lb.
250	26	2000	2. 0	1.5 x 2″	3–32″	5 lb.
300	25	2250	3. 0	2 x 2″	1–8″	6 lb.
400	24	2250	4. 0	2 x 2.5″	1–8″	7 lb.
500	23	2500	6. 0	2.5 x 2.5″	1–8″	10 lb.
750	21	3000	7. 5	2.5 x 3″	1–8″	14 lb.
1000	20	3000	------	3 x 3″	1–8″	18 lb.

TABLE IV

The data in TABLE IV (except for the data on the bare wire) are close approximations only, the thickness of the insulation on wire manufactured by different concerns being non-uniform, and the figures given being average.

By winding a single layer (two or three inches in length) around a spool, the turns per linear inch of winding space can be accurately determined.

B & S Gauge #	CM Area	OHMS PER 1,000 FEET	FEET PER LB.	
			DCC	SCC
8	16, 510. 00	0. 6405	019. 6	19. 9
9	13, 090. 00	0. 8077	024. 6	25. 1
10	10, 380. 00	1. 0180	030. 9	31. 6
11	8, 234. 00	1. 2840	038. 8	39. 8
12	6, 530. 00	1. 6190	048. 9	50. 2
13	5, 178. 00	2. 0420	061. 5	63. 2
14	4, 107. 00	2. 5750	077. 3	79. 6
15	3, 257. 00	3. 2470	097. 3	100. 0
16	2, 583. 00	4. 0970	119. 0	124. 0
17	2, 048. 00	5. 1630	150. 0	155. 0
18	1, 624. 00	6. 5100	188. 0	196. 0
19	1, 288. 00	8. 2100	237. 0	247. 0
20	1, 022. 00	10. 3500	298. 0	311. 0
21	810. 10	13. 0500	370. 0	389. 0
22	642. 40	16. 4600	461. 0	491. 0
23	509. 50	20. 7600	584. 0	624. 0
24	404. 00	26. 1700	745. 0	778. 0
25	320. 40	33. 0000	903. 0	958. 0
26	254. 10	41. 6200	1, 118. 0	1, 188. 0
27	201. 50	52. 4800	1, 422. 0	1, 533. 0
28	159. 80	66. 1700	1, 759. 0	1, 903. 0
29	126. 70	83. 4400	2, 207. 0	2, 461. 0
30	100. 50	105. 2000	2, 534. 0	2, 893. 0
32	63. 21	167. 3000	3, 137. 0	4, 414. 0
34	39. 75	266. 0000	6, 168. 0	6, 400. 0
36	25. 00	423. 0000	7, 877. 0	9, 846. 0
38	15. 72	672. 6000	10, 666. 0	13, 848. 0

TABLE V

TURNS PER LINEAR INCH OF WINDING SPACE (APPROXIMATE)

B. & S. GAUGE #	DCC	SCC/DSC	ENAMEL	ESCC	SSC
08	6.8	6.9	-------	-------	-------
09	7.6	7.6	-------	-------	-------
10	8.5	8.5	9.6	9.2	-------
11	9.5	9.6	10.4	10.2	-------
12	10.6	10.8	11.4	11.4	-------
13	11.8	12.0	12.6	12.7	-------
14	13.1	13.4	14.0	13.1	-------
15	14.6	14.9	16.0	15.7	-------
16	16.4	16.7	18.0	17.5	19.2
17	18.1	18.8	21.0	19.2	21.2
18	20.0	21.0	23.0	21.4	23.6
19	21.8	23.6	27.0	23.6	26.0
20	23.9	26.4	29.0	26.9	29.4
21	26.2	29.7	32.0	29.8	32.8
22	28.5	32.0	36.0	32.8	36.5
23	31.1	34.3	40.0	36.1	40.6
24	33.6	37.7	45.0	39.7	45.3
25	36.2	41.6	50.0	43.6	50.3
26	39.9	45.3	57.0	48.4	55.5
27	42.6	49.4	64.0	52.6	61.8
28	45.5	54.0	71.0	57.5	68.5
29	48.0	58.8	81.0	62.5	75.2
30	51.1	64.4	88.0	68.0	83.4
32	60.2	75.0	120.0	79.4	100.0
34	68.6	87.6	140.0	91.8	120.0
36	78.5	101.0	190.0	104.0	143.0
38	89.1	115.0	205.0	118.0	167.0

TABLE VI

TURNS PER SQUARE INCH OF WINDING SPACE. (SOLID LAYER WINDING)

Deduct 10% from these figures to allow for spacing required for hand winding

B & S GAUGE NO.	DCC	SCC DSC	SSC	EN-AMEL	ESCC	SILK AND EN-AMEL
08	45	47	------	------	------	------
09	57	59	------	------	------	------
10	71	73	------	92	84	------
11	89	92	------	108	105	------
12	112	116	------	130	130	------
13	139	144	------	150	161	------
14	171	180	------	194	199	------
15	211	220	------	254	248	------
16	268	278	368	322	304	------
17	325	352	449	438	374	------
18	400	440	560	530	455	------
19	470	550	670	725	555	------
20	566	695	895	840	720	810
21	680	875	1075	1020	890	1010
22	810	1020	1350	1290	1075	1230
23	960	1170	1650	1595	1310	1510
24	1125	1416	2045	2015	1575	1860
25	1310	1715	2515	2495	1910	2290
26	1580	2050	3100	3240	2310	2830
27	1805	2425	3810	4075	2770	3460
28	2060	2900	4700	5000	3300	4200
29	2300	3450	5650	6550	3900	5100
30	2600	4150	6950	7750	4650	6200
32	3600	5600	10000	14400	6300	8900
34	4700	7650	14400	19600	8300	12600
36	6150	10200	20400	36100	10700	17300
38	7900	13200	27800	42000	13900	23700

CHAPTER 9

ELECTRIC PROPELLERS

SHIFTING GEARS ON AIRCRAFT

What do you do when the traffic light turns green? No! "Blow my horn at the dumb ape in front of me" is not the right answer! You shift into LOW, SECOND, HIGH. And that's just what an airplane pilot does when he gets the green light from the control tower. He sets his electric propeller switch to LOW PITCH, so that the blades will take SMALL bites out of the air and gives him lots of pull at HIGH engine speed. But when he's up to his altitude, and is cruising along looking things over, he switches the propellers to HIGH PITCH, so the blades will take BIG bites of air. And he revs his engine DOWN to cruising speed. Look at figure 115, and you'll see how the blades look at HIGH and LOW pitches.

The propellers on many Navy flying boats can even be put into REVERSE pitch, so the pilot can turn sharply on the water and maneuver his plane right in against the pier without help from small boats. And pilots can FEATHER their propellers, or turn the blades around with the edge facing forward, so that the propellers won't act as windmills in case of engine failure, and won't turn the engine over by air pres-

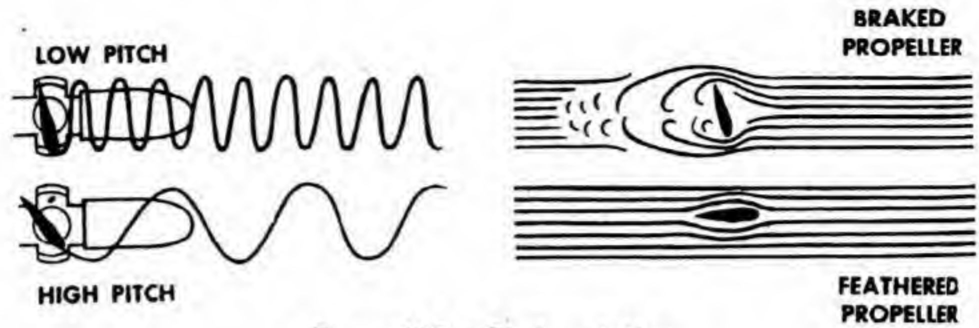


Figure 115.—Pitch variation.

sure. This windmilling is bad for dead engines, and also cuts down the ability of the plane to fly home with one engine dead.

There's another useful gadget for aircraft—the CONSTANT SPEED PROPELLER. This device contains

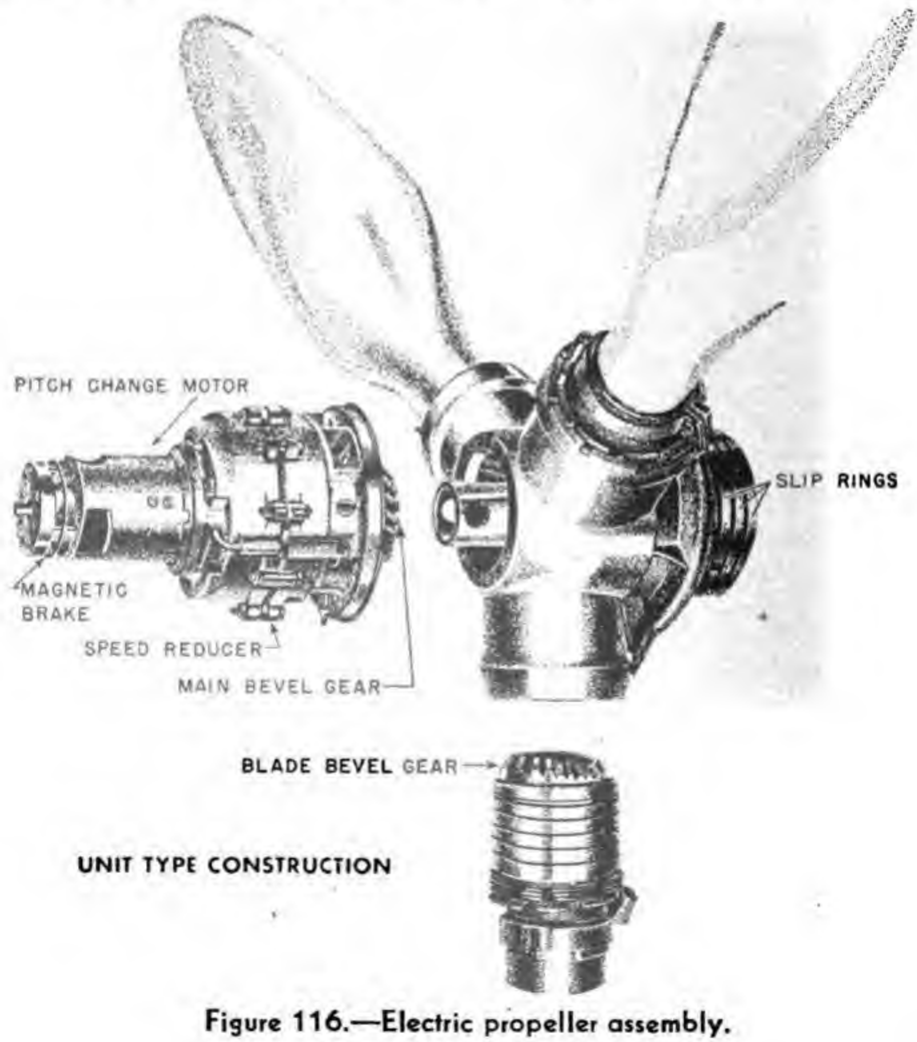


Figure 116.—Electric propeller assembly.

an oil-pressure governor which changes the propeller angles from low to high, or back to low as the load or the engine speed vary. The engine rpm are kept constant at whatever speed the pilot selects.

In general, the electric propeller is made up of the hub assembly, blade assembly, and power unit. Look at figure 116. Your main interest as an electrician will be in the power unit, which is made up of the electric drive motor, electric brake, speed reducer, and power gear assembly.

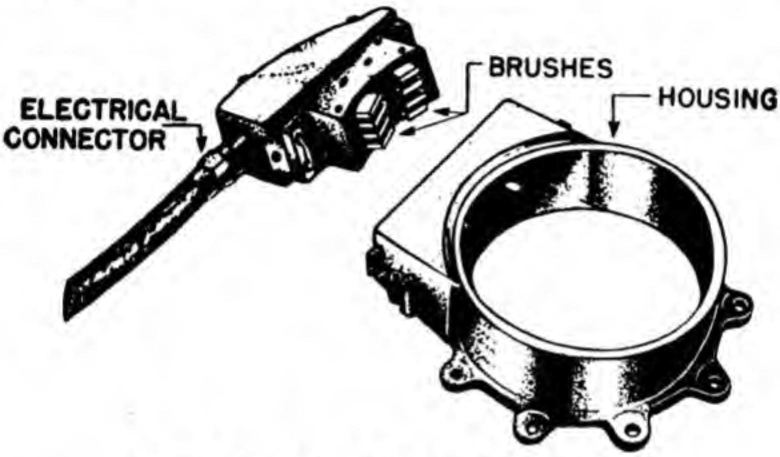


Figure 117.—Brush holder and housing.

The electrical circuits from the instrument panel selectors are carried out into the revolving propeller assembly by means of brushes on the engine nose—see figure 117—in contact with four bronze SLIP RINGS. They are at the right on figure 116. These slip rings are mounted on the propeller hub, and are insulated from the hub and from each other. From the slip rings, the electrical circuits are carried by brass rods through the hub to the connections on the PITCH CHANGE MOTOR.

PITCH CHANGE MOTOR

The pitch change motor actually does the turning of the propeller blades to the desired pitch angle. It connects through a speed reducer to the bevel gears

which rotate the blades from low to high or feather or reverse. The motor is a 12-volt, SERIES type, with TWO field windings to allow it to rotate in either direction. It is mounted in the nose of the propeller hub, along with the planetary-gear SPEED REDUCER, which reduces the high speed of the motor to the relatively low speed of the blades as they are rotated to change pitch.

PROPELLER ANGLE-LIMIT SWITCHES

On the speed reducer, you will find three, or even four, PROPELLER ANGLE-LIMIT SWITCHES. Their job is to stop or limit the rotation of the electric pitch change motor when the propeller blades have reached the blade angle selected by the pilot. Look at figure 118. The limit switches are operated by arms riding on cams which are attached to the main drive gear of the speed reducer. When the cam has been rotated to a certain point and the blades are at the selected pitch, the cam lifts the proper contact arm, which opens the circuit and stops rotation of the pitch change motor and the blades. The limit switches are spring-loaded, and are the low-angle limit switch, high-angle limit switch, and feather-angle limit switch. Some Navy multi-engine flying boats have a fourth—the negative-angle limit switch.

THE MAGNETIC BRAKE

On the left side of figure 116, you will find the MAGNETIC BRAKE. Solenoids on the brake are connected in series with the pitch change motor. When current flows to the motor to change the blade angle, current also flows to the solenoids and causes them to release the spring-loaded brake plate. The motor can then change the pitch angle. As soon as the blades reach the selected angle, the propeller angle-limit switches open the circuit to the motor and the

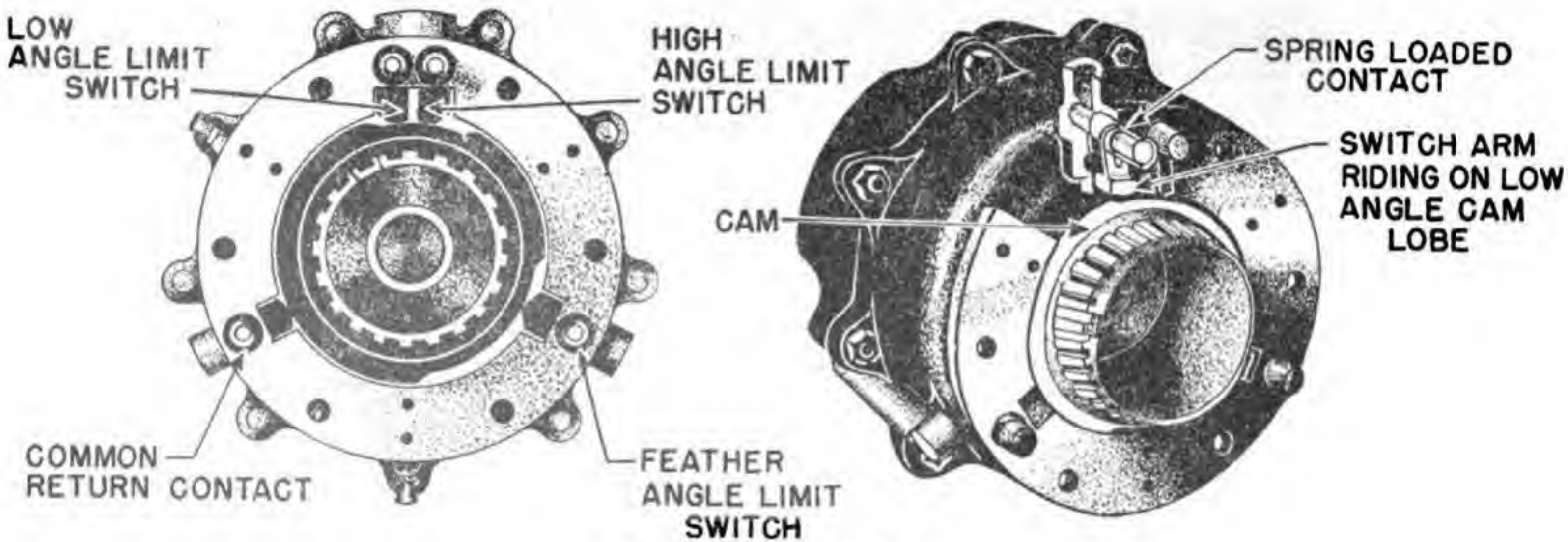


Figure 118.—Limit switches.

magnetic brake. The motor stops, and the brake solenoids are de-energized. The springs set the brake tight, and the blades cannot rotate accidentally nor drift out of pitch.

In case the electrical system fails, the blades are still locked tight in position and cannot change pitch accidentally.

HOW PROPELLERS ARE CONTROLLED

Consider first the operation of a propeller with a SIMPLE control circuit. Look at figure 118. Although this is not a conventional circuit, you could use it with a CONTROLLABLE PITCH propeller.

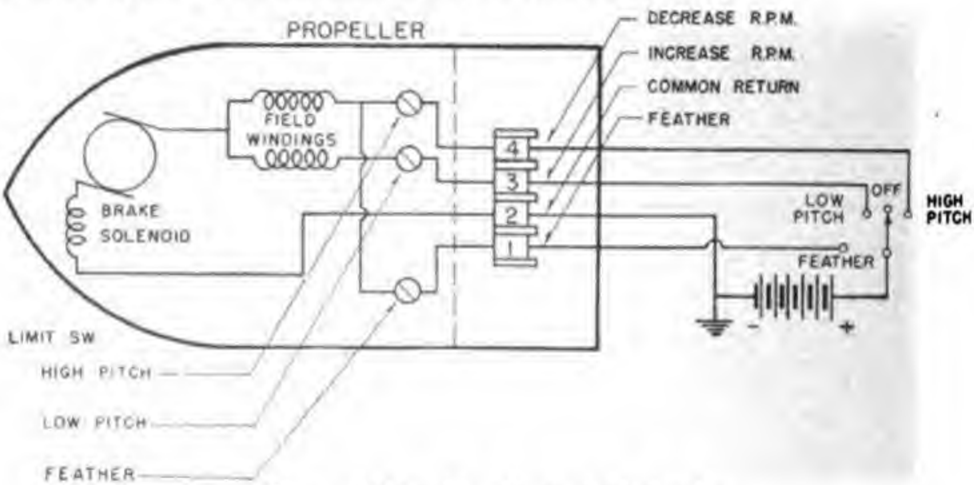


Figure 119.—Simple control circuit.

Shift the propeller into low pitch. When you set the switch in the low pitch position, the circuit from the battery to the power unit is completed. Current flows through the lower winding of the pitch motor, through the pitch motor armature, and the brake solenoid. When the current energizes the brake solenoid, the solenoid attracts the brake diaphragm. The force of the attraction is enough to overcome the tension of the brake springs, thereby releasing the brake disk assembly.

The pitch-change motor armature will now rotate freely. The armature torque is transmitted through

the speed reducer to the power gear, which in turn is geared to the propeller blades, causing them to rotate. As soon as the blades have rotated to a predetermined value of minimum pitch, the low-angle cam lobe opens the low-angle limit switch, breaking the circuit. The pitch motor now stops.

The brake diaphragm is no longer attracted by the brake solenoid. The pressure of the brake spring against the brake disk assembly sets the brake. Due to the high gear-ratio of the blade to the pitch motor armature and due to the friction of the brake, the pitch setting cannot slip nor change.

To change the propeller to high pitch, set the control switch in high position. The power unit operates exactly the same as before, except that the upper field is now being used. See figure 119. The motor rotates in a reverse direction. When the blade reaches a position of maximum allowable pitch, the high-angle limit switch opens the circuit.

From figure 119, you can see that the electrical circuit in the feathering position is the same as for high pitch, except that the limit switch is set so that the blades will rotate to a position in which they offer the least wind resistance to the air flow.

CONTROL SYSTEM

Here's how the constant speed control system works. To begin with—all aircraft engines are designed to operate under a loaded condition. In other words, they must have a load to oppose the revolutions or torque of the engine. If you removed the propeller, the engine would immediately build up speed in much the same manner as a series electric motor. At full throttle, and with no load, an aircraft engine would probably destroy itself by vibration and centrifugal force.

An engine will develop its maximum power near its maximum speed of rotation. This maximum

speed of rotation, or rpm, must be kept at a safe value. This is done by the low-angle limit switch. When the propeller blades are rotated to a position of minimum allowable pitch angle (therefore the maximum allowable rpm of the engine), the limiting switch opens, breaking the electric circuit. The opening of the circuit and the braking action of the magnetic brake immediately stops the pitch angle motor.

To maintain constant rpm with increasing propeller pitch, you need increased engine power. This is because the propeller will take a greater bite of air and is therefore producing more work. Thus, the maximum high-angle setting of the propeller blades is dependent upon the size of the blades and the power of the engine. In full high pitch, the engine must be able to turn the propeller at a speed sufficient to keep the airplane flying. In order not to exceed this maximum high pitch, a high-angle limit switch has been installed in the propeller. This switch operates just the same way as the low-angle limit switch.

Each propeller has been designed and adjusted to operate with a certain type of aircraft and engine. The high and low-angle switches have been adjusted similarly. Therefore, you MUST NOT SWAP THE PROPELLER TO A DIFFERENT TYPE PLANE WITHOUT READJUSTING THE LIMIT SWITCHES.

The control system of the electric constant speed propeller changes the pitch setting of the propeller automatically. Any tendency of the engine to increase or decrease its speed of rotation under various loads is met by a corresponding increase or decrease in propeller pitch. Constant rpm and power output are maintained.

A constant speed governor, a relay, a cockpit governor control, and suitable switches and wiring make up the control system. A thermal overload in

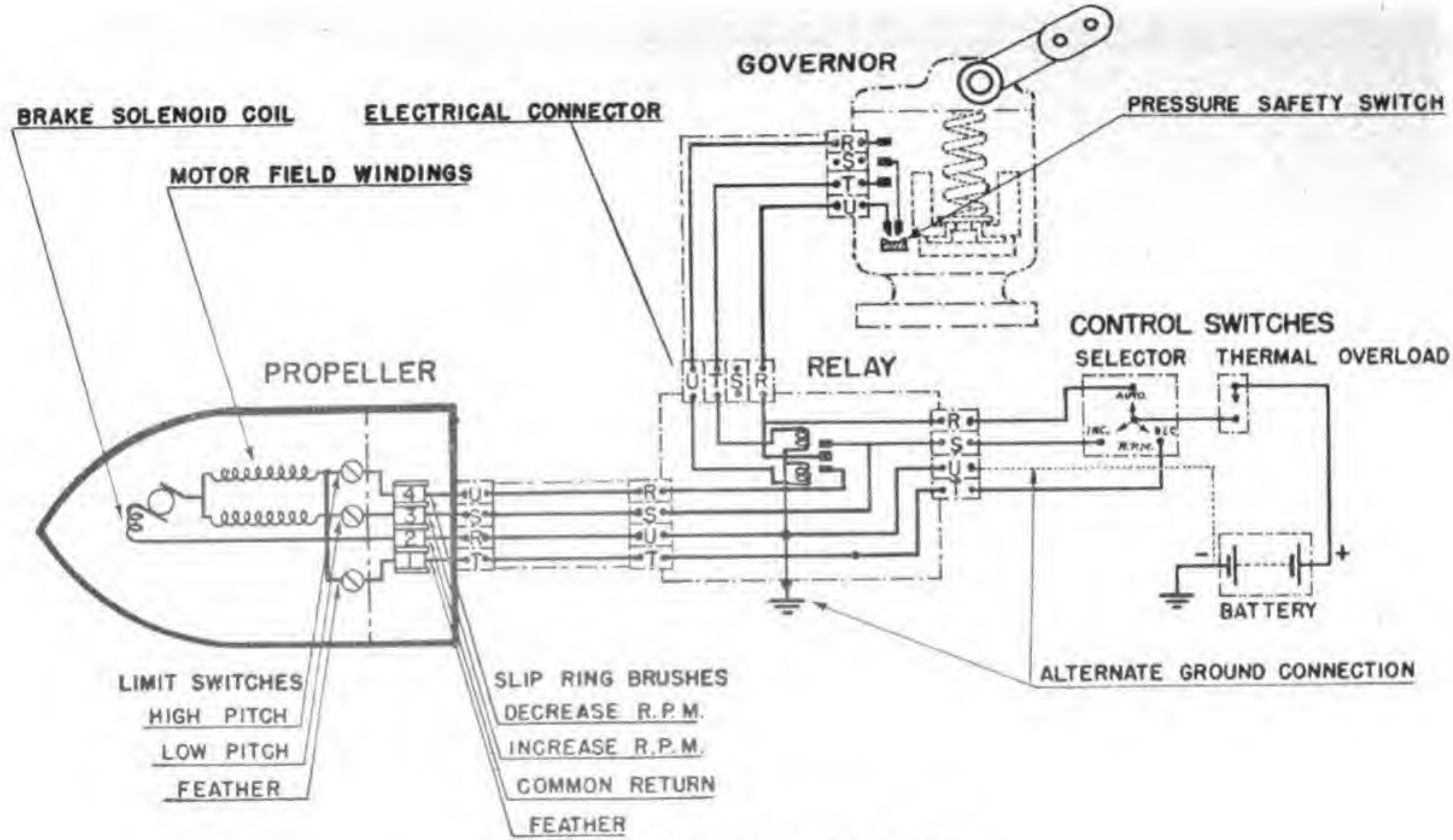


Figure 120.—Single engine wiring diagram.

the battery circuit protects the electrical circuits from overload, shorting, or grounds.

Figure 120 shows the schematic diagram of a complete propeller and control system for a single-engine airplane. You can use either AUTOMATIC or manual control of the propeller pitch. In order to avoid confusing the pilot, the control switches have been marked according to what they do. Instead of high pitch, they are marked DECREASE RPM, and so on. The operation of this circuit, when controlled manually, is similar to the simple circuit just discussed. When the control is thrown to the automatic position, the propeller pitch is regulated by the PROPORTIONAL GOVERNOR, and its RELAY.

The relay prevents the control contacts in the governor from carrying the full load current of the pitch motor. In effect, the relay duplicates the action of the governor contacts. It is a single-contact, double-throw relay. The direction of the relay armature is controlled by the relay solenoids. The solenoids in turn are controlled by the governor contacts.

PROPORTIONAL GOVERNOR

Look at figure 121 for a diagram of the proportional governor. The governor is usually mounted on the nose of the airplane engine, and is essentially an oil-pressure-operated electric double-pole switch which controls current in the circuit to the PITCH CHANGE MOTOR on the propeller. The fly-balls in the governor are rotated by a power-takeoff from the engine. Variations in engine speed cause these fly-balls to move up or down and control an oil-pressure valve which closes the electric contact switches connected to the pitch change motor.

In case of OVERSPEED, the fly-balls are thrown outward and oil pressure moves the electric contact switch upward to turn the current into the pitch

change motor fields that rotate the motor to increase the propeller angle. This increases the bite of air taken by the propellers, and causes the rpm to drop. If the engine speed falls off, the revolving fly-balls move in, oil pressure moves the electric contact downward to put current through the winding of the pitch change motor that decreases the propeller angle. Less bite is taken, and the rpm increase.

To permit finer and closer control of engine speeds, the electrical contacts are mounted on a cam-driven shaft that is driven off the same shaft as the fly-balls. By this arrangement, the DECREASE RPM and IN-

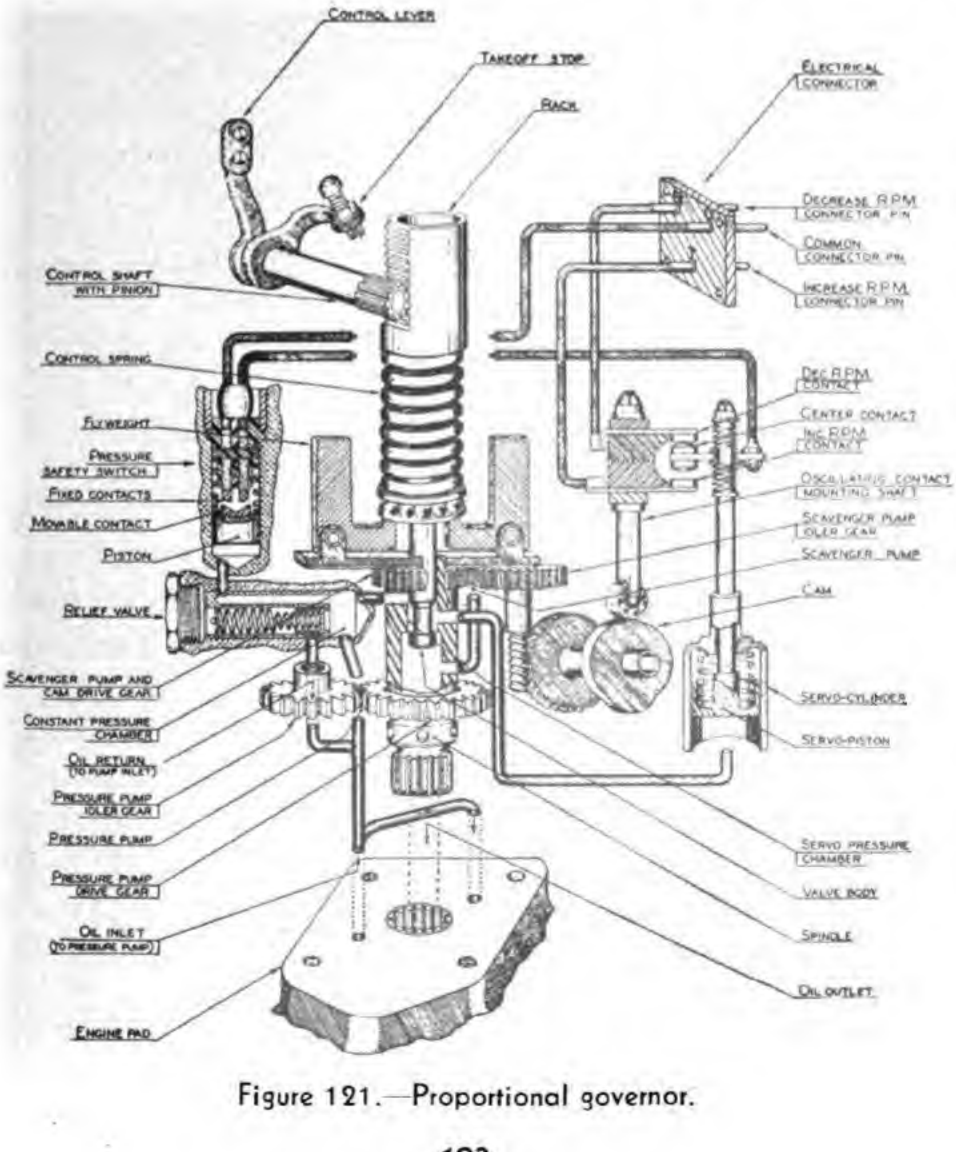


Figure 121.—Proportional governor.

CREASE RPM contacts cannot touch the center contact when it is in the neutral position. As the engine speed increases or decreases slightly, the center contact moves toward the DECREASE RPM or the INCREASE RPM contact, and is touched by this outer contact momentarily each time the cam motion brings the outer contact toward the center contact. Thus, for a slight increase or decrease in speed, the amount of blade angle correction brought about by momentary contact is sufficient to supply the exact correction for the off-speed condition. For great off-speed conditions, the center contact will move farther toward either of the oscillating contacts, thereby closing the circuit for a longer time. This continues until finally the two are making continuous contact. When off-speed conditions exceed approximately 60 rpm above speed or 90 rpm below speed, continuous contact is established.

FEATHERING AND REVERSE PITCH INSTALLATIONS

Some installations make use of the FEATHER feature. In this case, a feather switch is used. In one position, this switch completes the normal propeller circuit, while in the other, it completes only the feather circuit.

To provide a rapid angle change during feathering and reversing operations, most installations use a voltage booster. This booster is a DYNAMOTOR which multiplies the propeller voltage during these operations. The rate of blade angle change thereby is increased to about four times the normal rate. A solenoid switch in the booster, connected in series with the feathering or reversing circuit, supplies the current to operate the booster. It also stops the booster when the feather or reverse setting is reached.

THE RELAY

The RELAY is the heavy-duty switch mechanism of the propeller control circuit. See figure 122. It carries the propeller operating current to the pitch change motor while the propeller is operating in

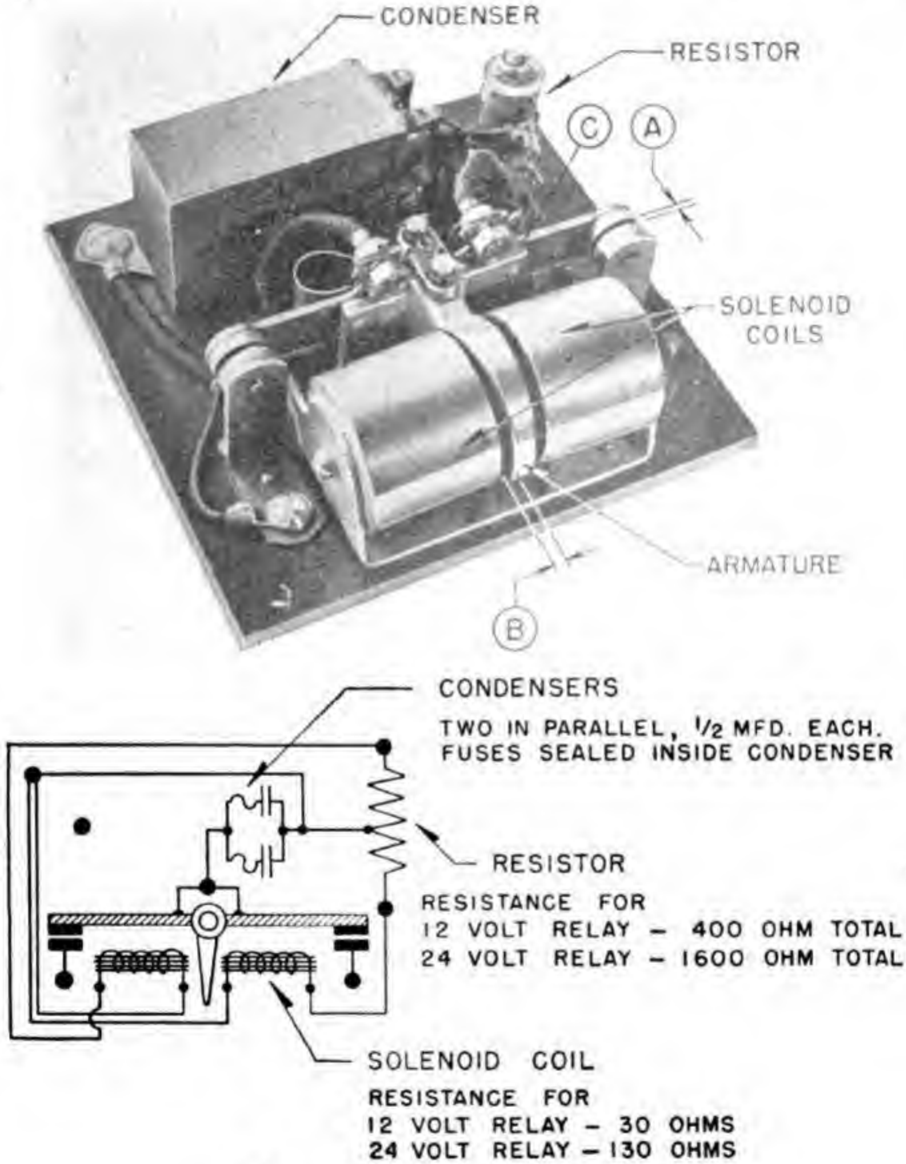


Figure 122.—Relay assembly.

AUTOMATIC CONTROL. A low amperage current, controlled by the governor contacts, energizes the relay solenoid coils. These energized coils act upon the armature of the relay. The armature causes the

heavy-duty relay points to close the propeller circuit.

The principal parts of a relay are—

An iron ARMATURE which carries the movable contact points while the stationary contacts are mounted on fixed brackets.

A pair of SOLENOID COILS placed so that one is on each side of the movable armature body.

A RESISTOR connected across the coil of the relay to dampen out small fluctuating currents. This dampening action increases the life of the points by causing the points to make solidly and break cleanly.

A CONDENSER assembly, consisting of two 0.5 mfd. condensers in parallel connected between the movable contacts and the return ground. These condensers smooth out electrical pulsations that may produce radio interference. These pulsations are voltage surges arising when the contact points break the propeller circuit.

Each condenser is equipped with an integral FUSE for circuit protection in case one of the condensers should develop a short.

The necessary wires, connectors, links, pins, springs, and mounting base.

CHAPTER 10

ELECTRICAL ORDNANCE EQUIPMENT

GUNFIRE AND BOMB RELEASE SWITCHES

When you've got a Zero lined up in your gunsight, or Tokyo filling up your bombsight—that's no time to be bothering with whether the guns will fire or whether the bombs will release. You want to press the button and hear the guns chatter or see the bombs fall away.

And that's why the GUNFIRE and BOMB RELEASE mechanisms are electrical—to insure split-second, ever-ready, fool-proof operation.

Look at figure 123 for a schematic diagram of a typical gunfire circuit. Electrically, it's just a simple single-wire circuit, containing firing solenoid, gunfire relay, control switches, and a source of current, along with the usual fuses and circuit breakers.

You actually fire the guns by pressing a button and feeding current through the wire coil wrapped around the soft iron core of a solenoid. A plunger inside the iron core is made to travel outward from the coil when you press the button and energize the solenoid coil. This outward travel of the plunger really presses the trigger in the same way that you pull the trigger of your .22 or shotgun with your finger.

The TRIGGER SWITCH, usually mounted in the end of the pilot's control stick, must be a lightweight, fast-acting switch that makes-and-breaks instantly to give good control of the gunfire. The trigger switch carries a small current, and has a spring action which makes the switch close instantly when the button is pressed part-way in. It also breaks-away instantly when the button is released.

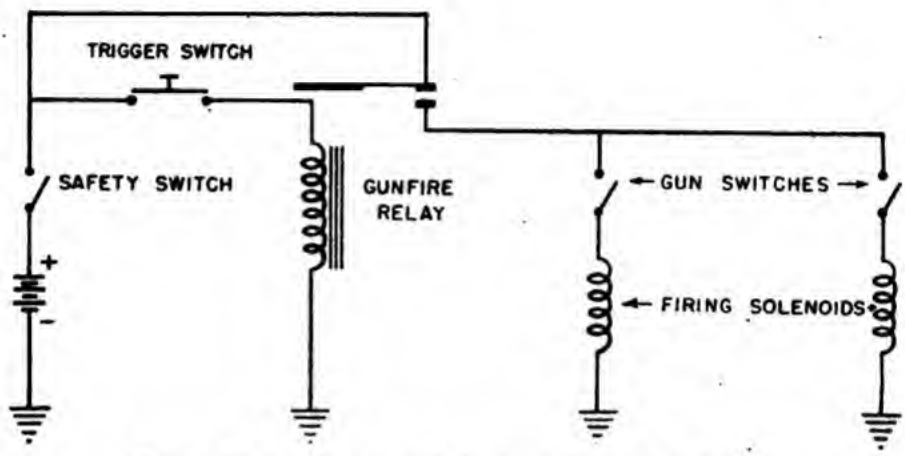


Figure 123.—Schematic diagram of gunfire circuit.

You'll also find the gunfire circuit carefully protected from accidental operation. There are SAFETY SWITCHES and GUN SWITCHES which open the circuit and prevent accidental firing of the guns when the plane is not on a mission. The SAFETY SWITCH is housed under a bright RED cover. The GUN SWITCHES, which allow the pilot to put certain guns into or out of the circuit as he wishes, are located close to the safety switch.

YOU have the responsibility of seeing that the gunfire mechanism on your aircraft is in READY condition at all times, that the pilot gets instant action from his guns when he presses the button. Check the fire-control system often, and pay special attention to the GUN FIRE RELAYS. They're the most likely to give trouble. Keep them CLEAN, FREE in action, and in good WORKING ORDER.

And now you've come to the electric POWER TURRET, which is a motor-driven housing to do accurate, high-speed elevating and training of the machine guns. It does these jobs in a hurry, and without any muscular effort from the gunner.

The turret housing, guns, gunner, and control mechanisms are all rotated around together in the turret, which rides on a circular track built into the airplane. The gear drive of the turret meshes with the gear teeth on the circular track. In addition to circular rotation of the whole turret, the guns can be elevated and lowered to give almost complete gunfire coverage of a hemisphere above the plane.

The electric turret is driven by two 24-volt motors—one motor driving the turret AROUND, or in AZIMUTH, and another motor ELEVATING the gun carriage. You use potentiometer controls to make the turret get-up-and-get in a hurry from a standing start. Look at the diagram in figure 124.

The turret drive uses the amplidyne generator in which a small amount of power (less than 1 watt) controls the entire generator output. Here's how it works. When you move the controller grip back-and-forth to rotate the turret, or move the controller grip up-and-down to elevate or lower the guns, you move one of the two potentiometer arms across the points of the potentiometer. Keep your eye on figure 124, so you don't get lost. As you move the controller grip, you move point *A* across the potentiometer winding and make the voltage between *A* and center-point *C* proportional to the distance that *A* moves away from *C*, either to right or left, or up or down.

This voltage is applied to the control field of the amplidyne generator through a part of voltage-divider resistor *D*. When the generator voltage starts to rise, the voltage in the lower part of voltage-

divider resistor D bucks the voltage between A and C, and reduces the control-field voltage. You soon reach a point where the difference in voltages A–C and E–F provides just enough control field to maintain the voltage of the amplidyne generator.

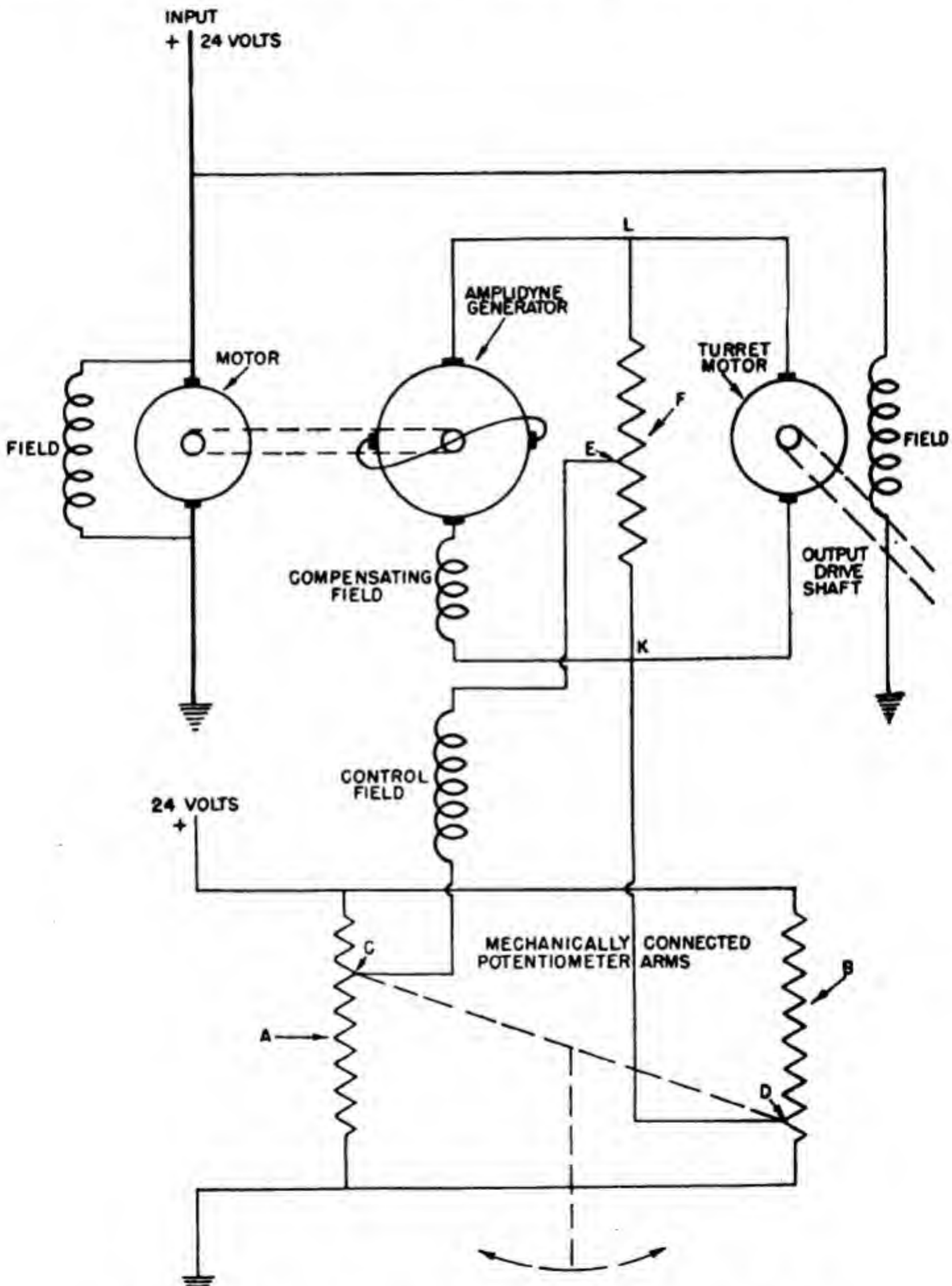


Figure 124.—Schematic diagram—power turret circuit.

Whenever you change the voltage *A–C*, by moving the controller grip, or change the voltage *E–F*, by changing the turret load, you also change the generator control-field voltage, and get a new generator-output voltage.

If you increase the turret-motor load, you reduce the voltage across *D–F*, and this lowers the voltage *E–F*. The lowering of voltages *D–F* and *E–F* increases the control-field voltage and increases the generator-output voltage. In this way, you tend to maintain a constant speed on the driver motor.

And that's how your turret is turned and elevated smoothly and at uniform speed, even from a standing start. There are two separate turret drives—one for rotation or azimuth, and another for elevation—but their electrical operation is identical.

FIRE INTERRUPTERS

You prevent a turret gun from firing into the tail surfaces and fuselage of its own plane by using a system of limit switches, called FIRE-INTERRUPTERS, operated by lugs or buttons on the turret circular track and elevation gear segments. When the guns are rotated or lowered so as to shoot into the plane itself, these fire-interrupters open the gun circuits and prevent the guns from firing.

In figure 125 you see the turret gun in different positions, illustrating the use of the fire interrupter switches. The gun is shown in an elevated position at the top of the figure. The ELEVATION INTERRUPTER SWITCH in this case would be CLOSED and the gun could be fired.

As you lower the gun to a horizontal position (second from top in figure 125) you'd fire into the vertical tail assembly. To prevent you from shooting the tails off too many planes, a cam attached to the ELEVATION SEGMENT GEAR will open the ELE-

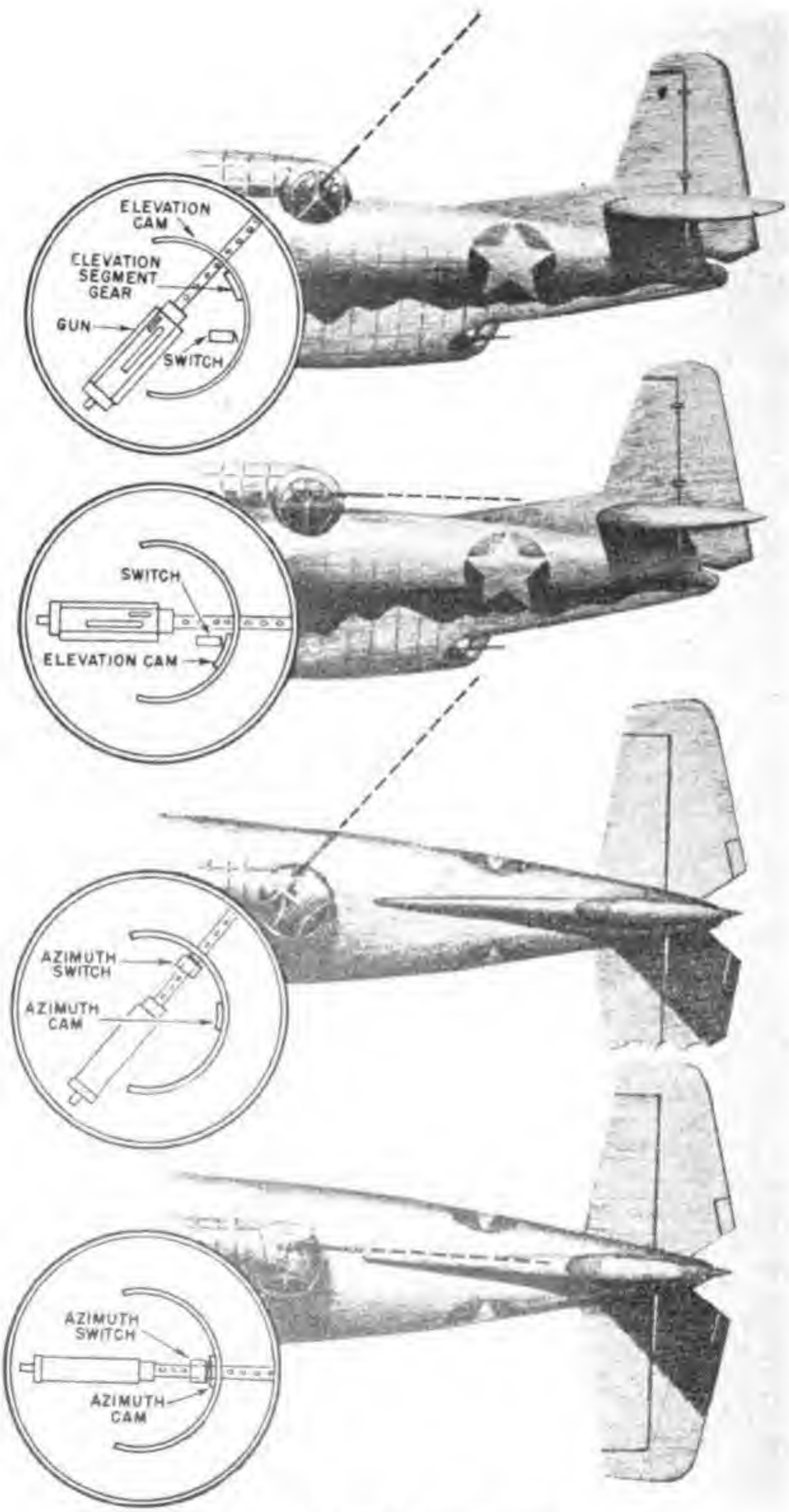


Figure 125.—Fire-interrupters.

VATION INTERRUPTER SWITCH and the gun will cease firing. This operation is shown in the diagram of the second figure.

In the third drawing from the top your gun is in position to fire starboard side of the plane. In this case, the AZIMUTH INTERRUPTER SWITCH would be closed and you could fire the gun. As you swing the gun so that its line of fire is aft, the azimuth cam will open the azimuth interrupter switch and the gun will cease firing until the tail surfaces are cleared.

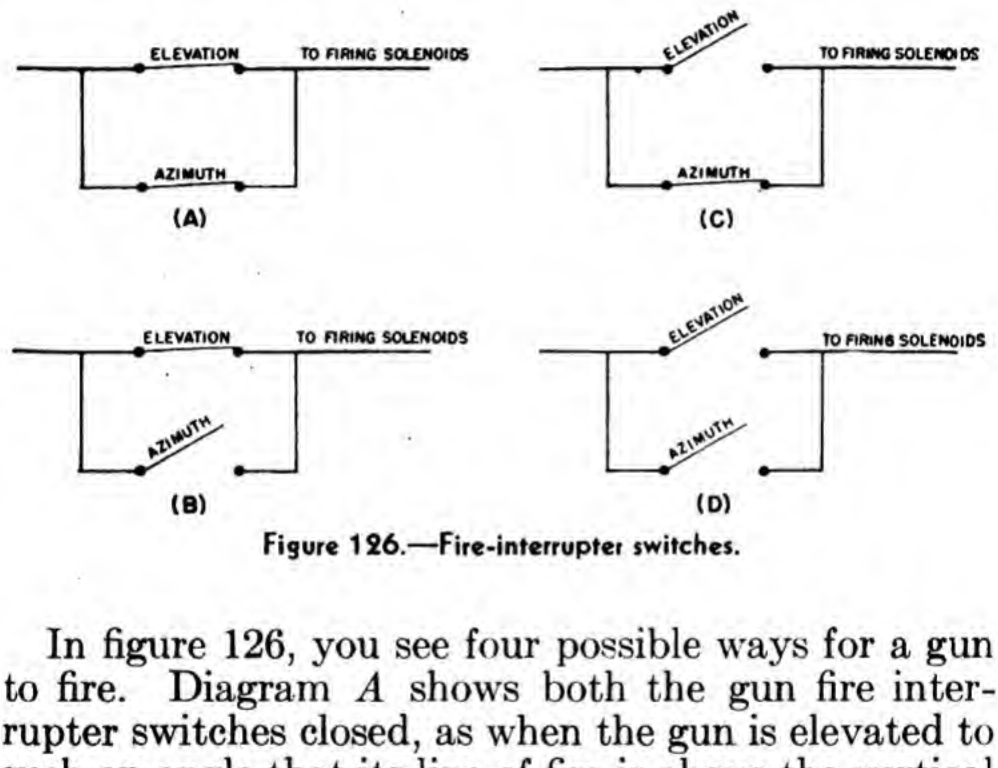
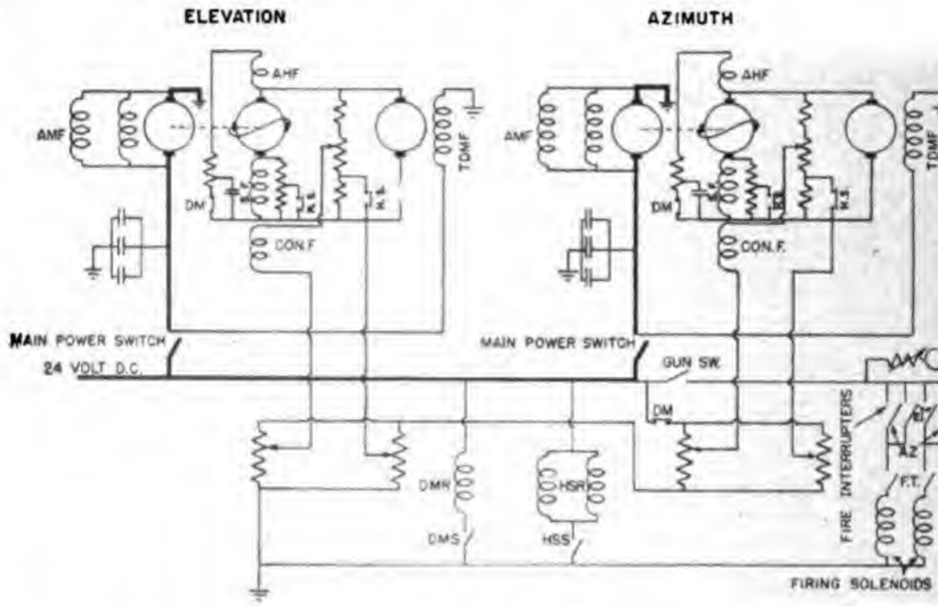


Figure 126.—Fire-interrupter switches.

In figure 126, you see four possible ways for a gun to fire. Diagram *A* shows both the gun fire interrupter switches closed, as when the gun is elevated to such an angle that its line of fire is above the vertical tail surfaces and is firing either to port or starboard. In diagram *B*, the gun is firing aft but at such an angle of elevation that its line of fire is above the vertical tail surfaces. Diagram *C* illustrates the gun being fired horizontally, but either to port or starboard. In diagram *D*, the position of the gun is such that both the azimuth and elevation interrupter switches are open. This means that the gun is in a horizontal position and pointing directly aft.

Each gun must have an azimuth and an elevation interrupter switch. If more than one gun is used, two switches are added to the circuit for each additional gun. The fire interrupter switches are located in the firing solenoid circuit.

In figure 127 you have the schematic wiring diagram of a two-gun power turret.



AHF ANTI-HUNT FIELD	DMS DEAD MAN SWITCH	HSS HIGH SPEED SWITCH
AMF AMPLIDYNE MOTOR FIELD	EL ELEVATION	LH LEFT HAND
AZ AZIMUTH	FT FIRING TRIGGERS	RH RIGHT HAND
DM DEAD MAN	GTS GUN TRIGGER SWITCH	SF SERIES FIELD
DMR DEAD MAN RELAY	HSR HIGH SPEED RELAY	TDMF TURRET DRIVE MOTOR FIELD

Figure 127.—Schematic diagram of two-gun Martin turret.

The MAIN POWER SWITCHES, in the AMPLIDYNE motor circuit, are of the THERMAL overload type. This type of switch opens automatically under dangerous overload conditions. You can close the switches again after a few seconds, but they will reopen if the overload condition still exists. Power switches must be opened or closed quickly to obtain a clean break or a positive contact, and prevent destructive arcing.

The GUN SAFETY SWITCH, located in the control power circuit, prevents accidental firing of the guns.

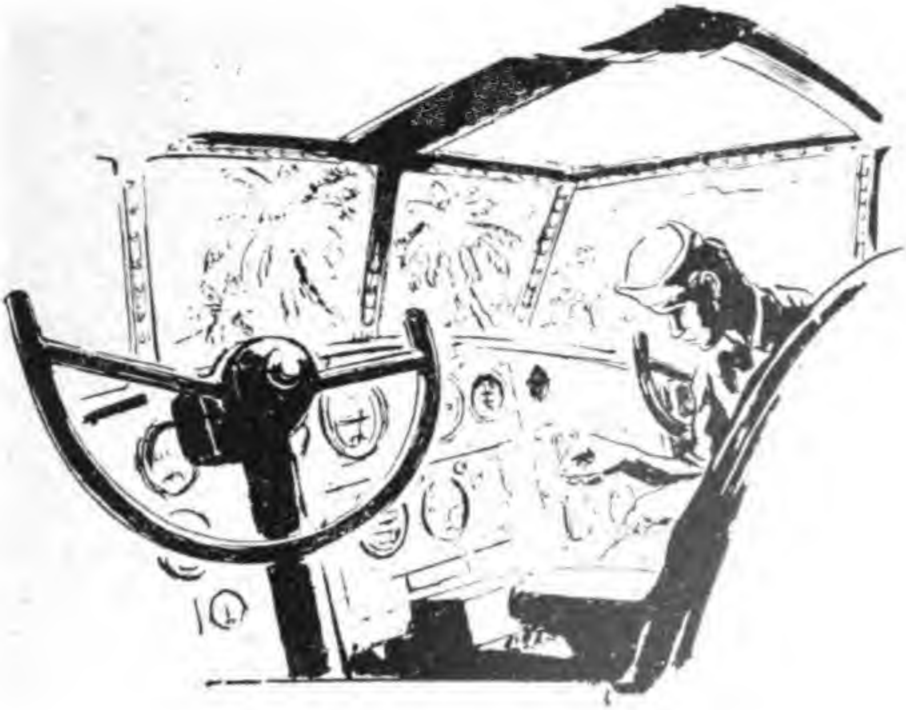
Neither gun can be fired unless the gun safety-switch is closed. To prevent accidental closing, this switch is covered by a guard.

The movement of the guns is controlled by the potentiometers shown in the diagram. The speed of rotation or the speed of elevation of the guns depends upon the arm settings of these potentiometers. You fire the guns by closing the firing triggers which operate the firing solenoids.

The HIGH SPEED SWITCH, in the control circuit, when closed, doubles the speed of the turret. The purpose of this control is to bring the turret quickly to a sight on the target. After this is done, the target is tracked by use of the normal speeds.

The DEAD-MAN SAFETY SWITCH is also in the control circuit. You must close this switch before the turret will rotate, elevate guns, or fire. It is an extra safety precaution to the plane and its crew.

The INTERRUPTER SWITCHES are also in the control circuit. The purpose and operation of these switches has already been given.



CHAPTER 11

AIRCRAFT ELECTRICAL CHECKS

KEEPING AIRCRAFT FLYING

All Naval aircraft are given periodic checks at regular intervals. These checks must be thorough. The airplane is grounded until the check is finished. The cooperation of the entire plane check crew is necessary so that the check will be thorough and finished as rapidly as possible.

In general, you will make checks after each 30, 60, and 120 hours of operation of the plane. Each squadron has made-up check-sheets for its particular type of plane. These sheets list in detail all the items you must check at that period. During this grounded period, you have an opportunity to make other necessary repairs which you cannot readily make when the plane is flying every day.

YOU'RE RESPONSIBLE, TOO

However, if at any time you discover an electrical unit that has become defective and is dangerous to the safe operation of the plane, notify the pilot and the Chief Electricians' Mate in charge of electrical checks immediately. The plane can be pulled off the flight schedule until repairs to the equipment are made.

Always remember that the lives of you and your shipmates depend upon the perfect operation of the electrical equipment.

Your first duty as AEM during the check period is to examine all electrical equipment. You must also cooperate with the other members of the check-crew in completing the entire inspection. A large part of your work during the check is in and around the engines. Since the AMM has work to do there also, you must plan your work so that you will not interfere with him. But your work must be done while the cowling is off the engine. Cooperate with the crew chief and let him know just what work has to be done to the electrical equipment. You will then help make the checking run smoothly and efficiently.

DAILY ROUTINE CHECK

1. Check operation of generator, with engine turning up at proper rpm.

2. Check operation of all electrical equipment, including lights, turret motors, flap motors, electrical instrument panels, or any other electrical equipment that can be ground-checked.

3. Make minor repairs, as necessary, between flights.

30-HOUR CHECK

1. Inspect batteries for gravity reading, corrosion, and loose connections.

2. Examine all lights and lighting systems.

3. Inspect all electrical wiring for proper insulation.

4. Check switches, relays, cutouts, instrument panels, and fuse boxes.

5. Inspect generator, motors, and solenoid releases, generator control box, and voltage regulator.

6. Check all electrical conduit for fraying or breaks, check tightness of all conduit connectors, open and inspect electrical junction boxes.

7. Put new wire, cotter keys, or elastic stop-nuts on all equipment checked or inspected.

8. After completing check, make a thorough operating check on all electrical equipment with engine turning up.

60-HOUR CHECK

(Add following to 30-Hour Check)

9. Check generator and starter motor for loose connections, and chipped, sticking, or broken brushes, check condition of commutators, blow out carbon dust with compressed air.

10. Inspect voltage regulator and reverse current relay, clean contacts if necessary, blow out voltage control box with compressed air.

11. Carefully examine all fuses, fuse blocks, and fuse boxes, replace fuses as necessary, fill spare fuse holders.

12. Replace light bulbs as necessary, fill spare light bulb containers.

13. Put new safety wire, cotter keys, or elastic stop-nuts on all equipment inspected. Renew as necessary on other equipment.

14. Complete check by operating and testing all electrical equipment throughout the airplane with the engine turning up.

120-HOUR CHECK

(Add following to 30- and 60-Hour Check)

15. If time allows and facilities are available, remove batteries from containers; send to battery shop for servicing; otherwise remove batteries from containers.

16. Inspect battery containers for corrosion; clean if necessary.

17. Replace batteries after thoroughly cleaning, grease battery terminals and connectors.

18. Renew all generator and motor brushes as required, blow out carbon dust with compressed air. If possible, remove generator from engine for shop checkup and operating test on generator test stand.

19. Clean generator and motor bearings, repack with fresh grease.

20. Inspect solenoids, check for ease of travel manually, check solenoid contactors for pits or burned spots.

21. Check voltage control box, voltage-regulator and reverse current relay. Clean contacts by drawing a clean piece of bond paper between the contacts while holding them closed by finger pressure. Blow out voltage control box with compressed air.

22. Make necessary adjustments to electrical equipment by removing to the shop when possible; otherwise make adjustments after check is completed and engine is turned up for final check.

23. Replace or renew all safety wire, cotter keys, or elastic stop-nuts where required.

24. Turn up engine and make all necessary electrical adjustments, note the operation of all equipment.

25. Ascertain that all electrical spares normally carried in the airplane are installed in proper place.

The amount of work involved and the items to be inspected will depend entirely upon the type and size

of aircraft being checked. The AEM—that's you—must remember that all items of electrical equipment, regardless of whether they happen to be listed on the check sheet or not, must be examined thoroughly at stated periods. This is in addition to the daily routine check. If this plan is strictly adhered to it will save many hours of work for the man who makes the very minor repairs that could be disregarded without endangering the airplane or its crew. This daily routine will make your work much easier, and you reduce the chance of having to ground an airplane for a major repair between check periods.

How Much Do You Know About—

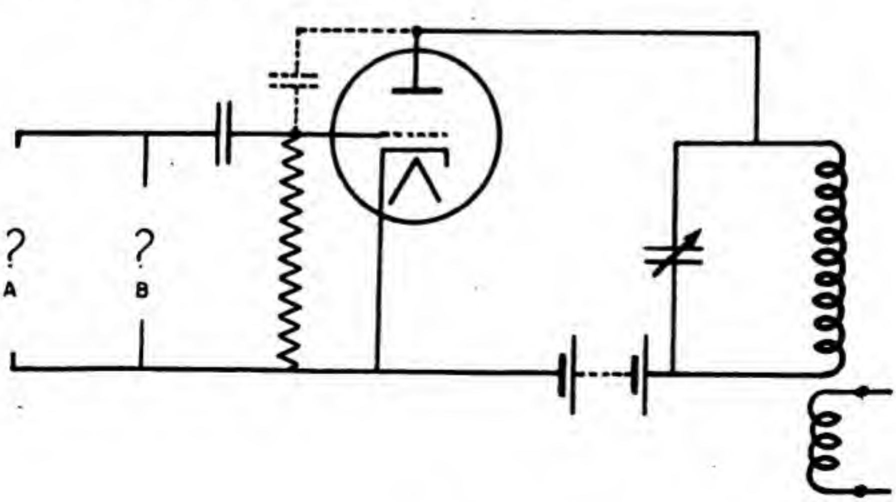
ADVANCED WORK IN AIRCRAFT ELECTRICITY

QUIZ

CHAPTER 1

VACUUM TUBES

1. What are the three elements of a triode vacuum tube?
2. The current through the plate circuit is produced by the flow of electrons from __________ to __________.
3. How can you speed up the flow of electrons across the space in a vacuum tube?
4. (*a*) What happens when you feed the positive cycle of an a. c. to the anode of a vacuum tube? (*b*) When you feed the negative cycle?
5. What purpose does the control grid serve in a vacuum tube?
6. What is the usual voltage rating of—(*a*) "A" batteries; (*b*) "B" batteries; (*c*) "C" batteries.
7. (*a*) What is the function of a grid leak? (*b*) How are grid leaks rated?
8. Why won't regular house current work in your vacuum tube circuit?
9. How do you convert pulsating d. c. to filtered d. c.?
10. What electrical property is used in the conversion of pulsating current to filtered current?



11. What two parts do you add to the vacuum tube circuit at the bottom of page 215 to make a simple oscillator?
12. In an oscillator circuit, energy from the__________ field of the condenser is converted into energy of the__________ field of the coil.
13. What are two ways of varying the frequency of an oscillator circuit?

CHAPTER 2

MEASUREMENT INSTRUMENTS

1. Current to be measured by a galvanometer flows through what part of the galvanometer?
2. Since the galvanometer is designed to measure very small currents, what do you connect across the terminals to make it measure large currents?
3. A galvanometer in a circuit reads 3 ma., and has 75 ohms resistance in it. You have a 1-ohm shunt across its terminals. What total current flows in the entire circuit?
4. You have a 6-volt voltmeter, with an internal resistance of 500 ohms. You know you've got to measure a voltage that is between 25 and 30 volts. What resistance should you add in series to the voltmeter circuit?
5. (*a*) To measure a LOW resistance accurately, how do you connect the voltmeter? (*b*) To measure a high resistance accurately by voltmeter-ammeter method, how do you connect the voltmeter?
6. The Wheatstone bridge is used to measure what?
7. The Wheatstone bridge has how many resistors? How many are fixed, how many variable, how many unknown?
8. In connecting up a Wheatstone bridge, what precaution must you take to avoid putting extra resistance in the circuit?
9. You make a megger by adding what equipment to an ohmmeter circuit?
10. What voltage can a megger usually impress on the circuit under test?

11. What prevents a d-c meter from operating on an a-c circuit?
12. Can you use a-c meters on d-c circuits?
13. (*a*) When you heat the junction of a thermocouple, what is the electrical result? (*b*) How is a variation of this result used by electricians?
14. What do you use a copper-oxide rectifier for?
15. You are handed a resistance of unknown value, to find out its value. By using a Wheatstone bridge, you find that the galvanometer registers zero when $R_1 = 5$ ohms, $R_2 = 3$ ohms, and $R_3 = 6$ ohms. What is the resistance of Rx in ohms?

CHAPTER 3

AIRCRAFT ELECTRICAL INSTRUMENTS

1. What are the three main parts of an aircraft electrical oil temperature indicator?
2. Three of the resistors in the Wheatstone bridge of the oil temperature indicator are located back of the indicator. Where is the fourth resistor located?
3. How do YOU, the AEM, repair a bad meter on the oil temperature indicator system?
4. What electrical principle is used in the cylinder temperature indicator?
5. The connection to the cylinder head is the__________ junction; the indicator meter is across the____________ junction.
6. How is voltage for the cylinder temperature indicator circuit supplied?
7. If you shorten or lengthen the copper-constantan leads from the engine to the indicator, what happens to the accuracy of the indicator? Why?
8. What does electric tachometer measure?
9. The electric tachometer operates on__________current supplied by the generator on the aircraft engine.

10. The synchronous motor of the electric tachometer rotates a magnet. What effect does this rotating magnet have on the metal drum?
11. What happens if the tachometer generator leads are shorted and the aircraft engine is started?
12. What are the two phases of current fed to the two windings of an engine synchronizer?
13. Which is the master engine of a four-engine aircraft?
14. The motion of the float in a gasoline tank causes what part of the selsyn to move up-and-down INSIDE the tank? What part to move OUTSIDE the tank? What electrical property makes the motion of this inner part move the outside part?
15. How many contacts are there on the resistance coil of a selsyn-fuel indicator?
16. The principle of operation of a selsyn indicator is based on creating a WHAT around the coils?

CHAPTER 4

KIRCHOFF'S LAW

1. State in your own words the principles of each of Kirchoff's two laws.
2. Suppose several currents meet at a junction. How must the current arrows be placed on the wires leading to a junction point?
3. (*a*) What sign precedes a RISE in potential? (*b*) What sign precedes a DROP in potential?
4. (*a*) What sign precedes the emf of a battery? (*b*) What sign precedes the value of *IR* of a battery?
5. Suppose you assume a direction of current flow around a closed circuit. (*a*) How will you know if you assumed the wrong direction? (*b*) When you correct the wrong direction of flow, will your answer change numerically?
6. (*a*) What is the polarity of the end of a resistor through which the current ENTERS? (*b*) What is the polarity of the end of a battery through which the current LEAVES?

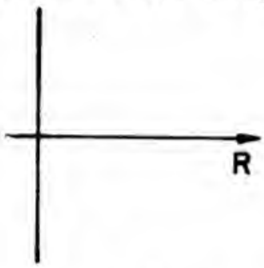
7. You have a generator, a battery, and a bank of lamps in a parallel circuit. The generator has an emf of 32 volts, with an internal resistance of 0.3 ohm. The battery is 24 volts, with an internal resistance of 0.2 ohm. The lamp bank has a total resistance of 125 ohms. Find: (*a*) Terminal voltage of battery; (*b*) terminal voltage of generator; (*c*) current through lamp bank; (*d*) current through battery circuit, and (*e*) current furnished by the generator.
8. (*a*) How much current flows through a battery that is floating on the line? (*b*) Suppose a battery floating on the line has an emf of 6 volts. What is the terminal voltage of the generator on this same circuit?
9. The voltage across each voltage-dropping resistor in a series is proportional to what?
10. (*a*) What does the bleeder resistor do? (*b*) What becomes of current sent through a bleeder resistor? (*c*) Bleeder current is usually what percent of the full-load current?

CHAPTER 5

THEORY OF A-C CIRCUITS

1. If you chart the voltage induced in a loop conductor as it turns 360° in a magnetic field, what type of curve will you get?
2. A two-pole generator rotating at 3,600 rpm produces 60-cycle current. A 12-pole generator would rotate how many rpm to generate 60 cycle current?
3. A certain a-c generator gives a peak voltage of 550 volts. What is its effective voltage?
4. An aircraft is flying due north at 150 miles per hour. The wind is blowing 30 mph from 50 degrees south of west. Draw the vector diagram and find the resultant speed and direction of the aircraft's course.
5. You want to add algebraically the output from two a-c generators. What must be the phase-relation of the two generators?

6. Generator A leads generator B by 30°. How can you add their outputs?
7. What three factors of an a. c. do you need to know to find the average power?
8. Each of these vector digarams indicates a circuit which contains (*a*) resistance, (*b*) inductance, (*c*) capacitance, (*d*) reactance, or (*e*) some combination of two of these. Identify the piece of electrical gear which is indicated by each vector diagram. (*Sketch*).



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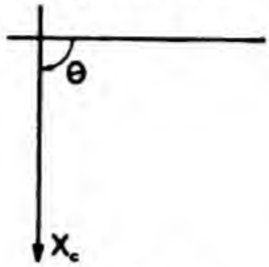

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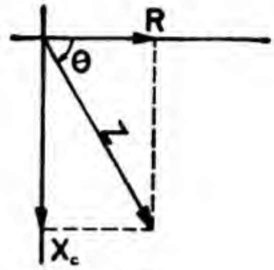

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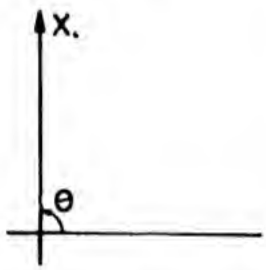

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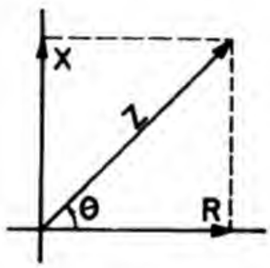

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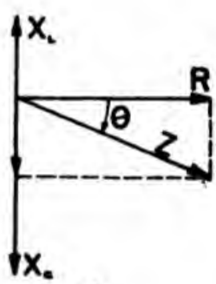

⑥

9. (*a*) When is a circuit resonant? (*b*) In a resonant circuit, what is the relationship of inductive reactance to capacitive reactance?
10. Is the total current in a parallel circuit a maximum or a minimum when the circuit is the resonance? (*b*) Which is it for a series circuit in resonance?
11. What are the two types of three-phase connections for a generator or motor?
12. How many degrees apart are the voltages of a 3-phase alternator supplying a balanced load?
13. (*a*) The line current in a delta-connected system is equal to how many times the phase current? (*b*) The line voltage of a Wye connected system is how many times the phase voltage?

14. Here are some formulas for electrical properties. What does each formula bring to mind?

(a) $2\pi fL$; (b) $EI \cos \theta$; (c) E^2/R; (d) P/EI; (e) $\frac{1}{2\pi\sqrt{fC}}$;

(f) $R_1 R_2 \sqrt{R_1 + R_2}$; (g) $\sqrt{R^2 + (X_L - X_C)^2}$; (h) $\frac{\text{Output}}{\text{Input}} \times 100$

CHAPTER 6

D-C ARMATURE WINDING

1. (a) What does rotating armature in a generator produce? (b) In a motor what does a rotating armature produce?
2. In a drum-wound armature, what is pole pitch?
3. If one side of a coil is under a south pole, the other side of the coil will be under what pole?
4. How many windings are there in each slot of a triplex-wound coil? In a simplex? In a duplex?
5. (a) When is a winding called "progressive"? (b) "Retrogressive"?
6. For a lap winding, the pitch must be such as to make the opposite sides of a coil lie under what poles?
7. How many times do you include each winding element in a lap-winding?
8. Does a lap-winding have to close on itself? Why?
9. How many paths are there through the armature of a simplex lap winding?
10. A simplex lap-wound armature has 18 slots and 2 pairs of poles. What is its average back pitch?
11. You find that a simplex lap-wound armature has 16 slots, and 4 poles, giving it an average back pitch of 8. Would you wind it at 8-pitch?
12. A winding which advances from pole to pole has what name?
13. What type of armature winding can have back pitch equal to front pitch?

14. In a simplex wave-wound armature, after passing once around the armature, the winding must fall how many elements to right or left of the element at which it started?
15. Why can't the commutator pitch of a wave-wound armature be equal to the total number of segments divided by the number of pairs of poles?
16. What is creepage in a winding?
17. For the same machine and the same number of armature conductors, the wave simplex winding will produce approximately how much voltage as a simplex lap-wound armature?
18. (*a*) A four-pole, triplex wave-wound armature has how many paths through it? (*b*) A two-pole, triplex wave-wound armature has how many paths through it?
19. A-C armature windings are similar to d-c windings, but usually much simpler. Why?

CHAPTER 7

MOTORS AND GENERATORS

1. On what does the generation of an emf depend?
2. On what part of the alternator is the voltage generating winding usually placed?
3. What motor does not have a commutator?
4. The difference in the speed of the rotor and the revolving magnetic field of an induction rotor is called what?
5. By what means are rotating fields produced in an induction rotor?
6. The speed of the rotating field of a rotor is called its what speed?
7. What is the speed of a 4-pole induction motor operating on 100-cycle current?
8. In an induction motor, torque is developed by the reaction between the field produced by the ----------------------- in the armature and the ----------- magnetic field.
9. What would happen if the armature of an inductor reached the rpm of the rotating magnetic field?

10. The rotating field produced by a. c. rotated at a what speed?
11. The amplidyne generator is essentially a ---------- ---------- excited generator.
12. For what type of service is the amplidyne generator most used?
13. The speed of a synchronous motor is constant if what is also constant?
14. (*a*) In the amplidyne generator, armature flux is at right angles to what?
    (*b*) The short-circuit axis flux is at right angles to what?
15. The voltage across the brushes of the ---------- ---------- of an amplidyne generator is very small in comparison to the ---------- ---------- of the machine.
16. What are the two ways to increase the amplification of an amplidyne generator?
17. What are the two fields in an amplidyne generator?

CHAPTER 8

POWER TRANSFORMERS

1. What are the two types of power transformers?
2. What data do you need to rebuild a transformer?
3. What is the purpose of using steel laminations in a transformer core?
4. You find some rusty steel plates of the correct gauge for transformer core laminations. What do you do about the rust?
5. What is the regulation of a transformer? How is it expressed?
6. What usually causes poor regulation?
7. You have a 110-volt 50-cycle transformer rated at 1,000 watts. You want to use it on a 110-volt, 25-cycle line. What will be its output voltage? Its wattage output?
8. The C. S. A. of a transformer is determined by knowing what three facts about the transformer?

9. You have a transformer with 24 volts across the primary and 120 turns of wire on the primary. The secondary has 2,500 turns on it. What is the output at no load?
10. For continuous service, what size wire in "circular mils per ampere" should be used? For intermittent service, what size may be used?
11. Design a transformer. Here are the specifications:

    Power output: 240 watts.
    Power input: 250 watts.
    Primary voltage: 24 volts.
    Secondary voltage: 500 volts.
    Frequency: 800 cycles.
    Duty: Continuous.

    You have on hand a used transformer core of silicon steel plates, with a C. S. A. of 2 square inches, and a window opening 3″ x 3″. For the primary, use DCC wire; for the secondary, use ESCC wire.
12. Which coil is wound next to the core?
13. Which voltage must the insulation between the layers withstand?
14. What do you use to waterproof transformer coils?

CHAPTER 9

ELECTRIC PROPELLERS

1. When the propeller blades take large bites of air, they are at what pitch?
2. What harm does "windmilling" of a propeller do?
3. By what device is the electrical circuit from the instrument panel carried into the revolving propeller assembly?
4. The pitch of the propeller blades is changed by what motor? How many field windings does this motor have, and why?
5. The magnetic brake on the adjustable pitch propeller does which one of these?—(Stops the airplane engine) (prevents the electrical energy in the propeller from affecting the compass) (keeps the landing wheel brakes

magnetized) (prevents the propeller blades from accidentally slipping out of the pitch selected by the pilot).

6. What device stops the pitch change motor when the proper pitch angle has been reached by the blades?
7. You have an Allison-powered P–39 with a badly damaged constant-speed electric propeller. In the storeroom is a complete constant-speed electric propeller assembly for a Hornet-powered P–47. (*a*) Why can't you use it, as-is, on the P–39? (*b*) How can you adapt the P–47 propeller assembly to fit the P–39?
8. How are the electric contacts in the proportional governor moved up or down as engine rpm vary?
9. The high current to the pitch change motor is carried through a heavy-duty what?

CHAPTER 10

ELECTRICAL ORDNANCE EQUIPMENT

1. In a gunfire circuit, the firing is done by pressing the trigger button, which does what in the circuit?
2. The safety switch box cover is painted what color?
3. What parts of the gunfire electrical system are most likely to give trouble, hence need frequent checking?
4. What is the voltage of the turret drive motors?
5. One turret drive motor drives the turret in ________________, the other in ________________.
6. How much power is used in the amplidyne generator to control the generator output?
7. You want to shoot the rudder off your own plane with your upper turret guns. The guns won't fire. Why?
8. What does the gun safety switch do? In what circuit is it located?
9. The main power switches are located in what circuit?
10. The high speed switch is in the ________________ circuit, and ________________ the speed of the turret to bring the guns to bear on a target.
11. Why is the amplidyne generator used in the turret drive circuit?

CHAPTER 11

AIRCRAFT ELECTRICAL CHECKS

1. A PB2Y–3 Coronado flying boat has been beached for repairs and check-up, and is ready to be returned to service. You discover that the electrical main fuel gauge is reading wrong, but to change it will delay returning the PB2Y–3 to service. What do you do?
2. Your DAILY check-up of electrical equipment includes which of these: (The generators and electrical panel instruments) (the generators only) (generators and light-bulbs) (generators and all electrical equipment that can be ground-checked).

ANSWERS TO QUIZ

CHAPTER 1

VACUUM TUBES

1. Filament, grid, plate.
2. Filament to plate.
3. (*a*) Add a "B" battery to the plate circuit of a diode tube, or (*b*) insert a grid and a "C" battery in the diode tube and make it a triode tube.
4. (*a*) Current flows from the plate to the filament as electrons move from filament to plate. (*b*) Nothing happens.
5. It controls the flow of electrons from filament to plate.
6. (*a*) 6 volts; (*b*) 45 volts; (*c*) 4.5 volts.
7. (*a*) To allow excess negative electrons to leak off the grid and back into the circuit on the positive grid cycle. (*b*) In megohms or millions of ohms of resistance.
8. Regular house current is 60-cycle, 110-volt a. c. A vacuum tube circuit calls for d. c., at probably 45 volts, 6 volts, and 4½ volts.
9. Run the pulsating d. c. through a filter choke coil.
10. Inductance.
11. (*a*) Inductance coil and (*b*) variable condenser.
12. *1*. Dielectric. *2*. Magnetic.
13. (*1*) Vary the capacity of the condenser.
    (*2*) Change the windings of the coil.

CHAPTER 2

MEASUREMENT INSTRUMENTS

1. The movable armature coil.
2. Shunt.
3. $(75\times3)+3=225$ ma.
4. 2,000 ohms.
5. (*a*) Directly across the resistance only.
   (*b*) Across the resistance AND the ammeter.

6. Resistance.
7. (*a*) Four; (*b*) Two; (*c*) One; (*d*) One.
8. Keep all contact points bright and clean.
9. Hand-cranked generator.
10. Usually 500 volts.
11. The alternations or reversals of current flow in a. c.
12. Yes, but not accurately. And, if the meter has a copper-oxide rectifier, you may burn it out.
13. (*a*) A voltage will be generated across the cold junction. (*b*) The hot junction is subjected to a current. A voltage can be measured across the cold junction.
14. To rectify a. c. to d. c.
15. $R_x = 10$ ohms.

CHAPTER 3

AIRCRAFT ELECTRICAL INSTRUMENTS

1. *1*. Bulb. *2*. Leads. *3*. Indicator.
2. Immersed in the engine oil in the engine crankcase.
3. YOU, the AEM, DON'T repair it. You replace it and send the bad meter to an instrument shop for repair.
4. Thermo-couple.
5. *1*. Hot junction, *2*. Cold junction.
6. By thermo-electrical action.
7. You upset the calibration of the instrument because you have changed the total resistance of the leads.
8. Engine rpm.
9. Alternating.
10. Makes it try to rotate.
11. The rotor may lose part of its magnetic flux, and the tachometer will read inaccurately.
12. Single-phase, and three-phase.
13. Left outboard engine.
14. *1*. A U-shaped magnet on the float lever. *2*. A diamond-shaped float. *3*. Magnetism.
15. Three: "Full", "Empty", and the intermediate points.
16. Magnetic field.

CHAPTER 4

KIRCHOFF'S LAW

1. Check your statements with Kirchoff's two laws on page 51.
2. So that the currents into the junction are equal to the currents flowing away from the junction.
3. (*a*) Plus. (*b*) Minus.
4. (*a*) Plus. (*b*) Minus.
5. (*a*) If your answer comes out negative. (*b*) No.
6. (*a*) Positive. (*b*) Negative.
7. (*a*) E_{bt}l $=27.174$ volts.
   (*b*) $E_{st}=27.174$ volts.
   (*c*) $I_L=.2174$ amps.
   (*d*) $I_b=15.87$ amps.
   (*e*) $I^G=16.087$ amps.
8. (*a*) None. (*b*) 6 volts.
9. The resistance of the voltage-dropping resistor.
10. (*a*) Stabilizes the voltage at the other resistor taps.
    (*b*) It is wasted as heat. (c) 5 to 10 percent.

CHAPTER 5

THEORY OF A-C CIRCUITS

1. Sine curve.
2. 600 rpm.
3. 388 volts.
4. 174 mph on a course 6°20′ east of due north.
5. They must be in phase.
6. By vectors.
7. Average current, average voltage, and the phase angle.
8. *1.* Resistance only.
   2. Capacitance only.
   3. Resistance and capacitance.
   4. Inductance only.
   5. Resistance and inductance.
   6. Resistance, inductance, and capacitance.

9. (*a*) When its resultant current is in phase with its line voltage.
   (*b*) The inductance is equal to the capacitance and lagging by 180°.
10. (*a*) Minimum. (*b*) Maximum.
11. Delta and Wye.
12. 120°.
13. (*a*) $\sqrt{3}$. (*b*) $\sqrt{3}$.
14. (*a*) Inductive reactance; (*b*) single phase power; (*c*) power; (*d*) power factor; (*e*) resonant frequency of a circuit; (*f*) total resistance; (*g*) impedance; (*h*) efficiency.

CHAPTER 6

D-C ARMATURE WINDING

1. (*a*) EMF. (*b*) Torque.
2. Distance between two adjacent poles on the stationary frame.
3. North.
4. Three; one; two.
5. (*a*) When the front pitch is LESS than the back pitch.
   (*b*) When the front pitch is GREATER than the back pitch.
6. Unlike.
7. Only once.
8. Yes. So that you will have two elements in each slot, and no empty slots.
9. As many as there are poles.
10. Nine.
11. No. Back pitch and front pitch must be an odd number. Use 9 for back pitch and 7 for front pitch.
12. Wave winding.
13. Wave.
14. Two.
15. The winding would close on itself after one passage around the armature.
16. The difference between calculated and actual pitch of a wave-wound armature.

17. Three times.
18. (*a*) 6. (*b*) 6. The number of poles has no bearing on the number of patches.
19. D-C machine requires complex connections to the same commutator bars. A-C machine doesn't. Also, to prevent excessive sparking of a d-c machine, you must use more coils of fewer turns each.

CHAPTER 7

MOTORS AND GENERATORS

1. The relative motion of a conductor and a magnetic field.
2. The stationary frame of the machine.
3. Induction.
4. Revolutions of slip.
5. By polyphase currents.
6. Synchronous.
7. 3,000 rpm.
8. *1*. Induced currents. *2*. Rotating.
9. There would be no cutting of conductors by flux, hence no torque would develop.
10. Synchronous.
11. Cross-axis.
12. Those jobs requiring high speed of response and high amplification of effort.
13. Frequency of applied emf.
14. Control field flux. Load axis.
15. Short-circuit axis; maximum output voltage.
16. Increase the short-circuit axis current either by (1) adding a shunt field in the short-circuit axis or (2) adding a series field.
17. Control field and load-compensating field.

CHAPTER 8

POWER TRANSFORMERS

1. Core and shell.
2. *1*. Voltage frequency. *2*. Primary voltage. *3*. Secondary voltage. *4*. Either the primary or secondary current.
3. To reduce eddy current losses.
4. Nothing. Leave it on the plates. It's excellent insulation between laminations.
5. The drop in secondary voltage from no-load to full load, in percent of full load. In percent.
6. Excessive resistance of the windings for the load, and excessive magnetic leakage caused by poor transformer design.
7. 82 percent of 110, or 90.2 volts. 82 percent of 1,000 watts, or 820 watts.
8. Frequency, core material, and power output.
9. 504 volts.
10. 1,500 CM per ampere. 1,000 CM per ampere.
11. (*a*) Core area: ok. (*b*) Turns per volt: 1.3 turns. (*c*) Turns on primary: 31. (*d*) Turns on secondary: 670. (*e*) Full-load current on primary: 10.4 amps. (*f*) Full-load current on secondary: 0.48 amp. (*g*) C. S. A. of primary wire: 15,600 CM, or B & S gauge #8 wire. (*h*) C. S. A. of secondary wire: 720 CM, or B & S gauge #21 wire. (*i*) Primary winding space: .75 sq. in. (*j*) Secondary winding space: .84 sq. in. (*k*) Total window space required: 1.59 sq. in. (*l*) Depth of windings: .63 inch, approx. (*m*) Insulation between windings: Layer of Empire cloth to hold 116 volts between primary and secondary layers.
12. Low voltage winding.
13. Full secondary voltage.
14. (*a*) A molten mixture of paraffin and beeswax, or (*b*) Shellac, but only if you can bake the coil in an oven after shellacking.

CHAPTER 9

ELECTRIC PROPELLERS

1. High.
2. Damages the dead engine, and reduces the ability of the plane to fly home with one dead engine.
3. Through slip rings and brushes.
4. Pitch change motor. Two, so it can rotate either forward or reverse.
5. Prevents the propeller blades from accidentally slipping out of the pitch selected by the pilot.
6. Limit switches.
7. No, because the engine-power characteristics of the two engines are different.
8. Adjust the limit switches to suit the power characteristics and requirements of the P–39 and the Allison engine.
9. By oil pressure, controlled by a flyball governor.
10. Relay.

CHAPTER 10

ELECTRICAL ORDNANCE EQUIPMENT

1. Energized the coil of wire around the soft iron core of the gunfire solenoid. The iron core moves out of the magnetic field, and fires the gun.
2. Red.
3. Gunfire relays.
4. 24.
5. Azimuth, elevation.
6. Less than one watt.
7. Fire-interrupter switches have de-energized the gunfire relays to prevent this.
8. Prevent accidental firing of the guns in the control power circuit.
9. In the amplidyne motors circuit. They open automatically.
10. Control. Doubles.

11. *1.* A small amount of controller power controls a large amount of driving power. *2.* The turret can get up to uniform speed in a hurry.

CHAPTER 11

AIRCRAFT ELECTRICAL CHECKS

1. Report the trouble at once to the pilot and the CEM. This trouble might well cause loss of the aircraft at sea, and danger to the crew.
2. Generators and all electrical equipment that can be ground-checked.

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